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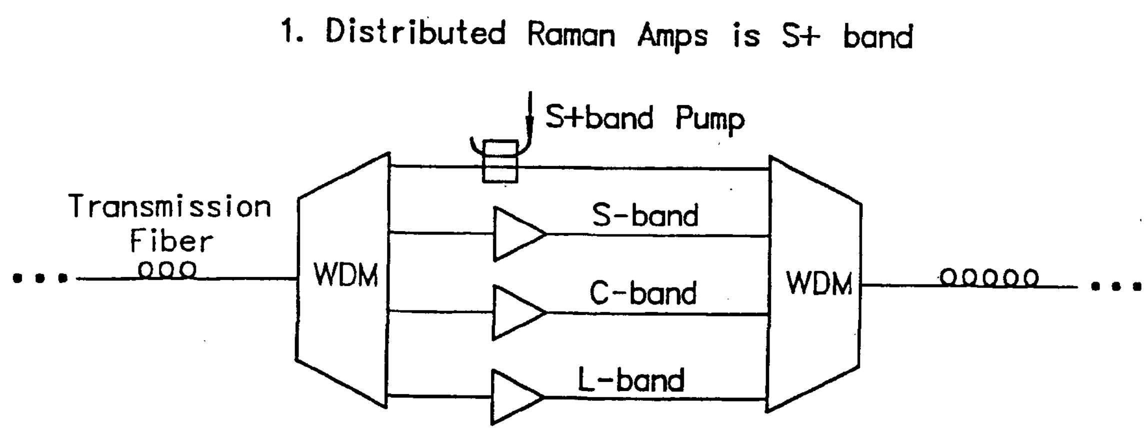
(54) Title: S^+ BAND NONLINEAR POLARIZATION AMPLIFIERS



(57) Abstract: An amplified broadband optical signal is produced in a transmission system. An optical signal is divided into a first beam and a second beam. The first beam has a wavelength less than a predetermined wavelength. The second beam has a wavelength greater than the predetermined wavelength. The first beam is directed to a transmission link in the transmission system. The transmission system includes a distributed Raman amplifier. The distributed Raman amplifier operates in the wavelength range less than 1480 nm. The second beam is directed to a second amplifier. The first and second beams are combined. An amplified broadband optical signal is produced.

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S$^+$ BAND NONLINEAR POLARIZATION AMPLIFIERS

FIELD OF THE INVENTION

The present invention relates generally to nonlinear polarization amplifiers, and more particularly to nonlinear polarization amplifiers used to amplify signals in the S$^+$ band, approximately ranging from 1430-1480nm.

BACKGROUND OF THE INVENTION

Because of the increase in data intensive applications, the demand for bandwidth in communications has been growing tremendously. In response, the installed capacity of telecommunication systems has been increasing by an order of magnitude every three to four years since the mid 1970s. Much of this capacity increase has been supplied by optical fibers that provide a four-order-of-magnitude bandwidth enhancement over twisted-pair copper wires.

To exploit the bandwidth of optical fibers, two key technologies have been developed and used in the telecommunication industry: optical amplifiers and wavelength-division multiplexing (WDM). Optical amplifiers boost the signal strength and compensate for inherent fiber loss and other splitting and insertion losses. WDM enables different wavelengths of light to carry different signals parallel over the same optical fiber. Although WDM is critical in that it allows utilization of a major fraction of the fiber bandwidth, it would not be cost-effective without optical amplifiers. In particular, a broadband optical amplifier that permits simultaneous amplification of many WDM channels is a key enabler for utilizing the full fiber bandwidth.

Silica-based optical fiber has its lowest loss window around 1550nm with approximately 25THz of bandwidth between 1430 and 1620nm. For example, Fig. 1 illustrates the loss profile of a 50km optical fibr. In this wavelength region, erbium-doped fiber amplifiers (EDFAs) are widely used. However, as indicated in Fig. 2, the absorption band of a EDFA nearly overlaps its the emission band. For wavelengths shorter than about 1525nm, erbium-atoms in typical glasses will absorb more than amplify. To broaden the gain spectra of EDFAs, various dopings have been added. For example, as shown in Fig. 3a, codoping of the silica core with aluminum or phosphorus broadens the emission

spectrum considerably. Nevertheless, as depicted in Fig. 3b, the absorption peak for the various glasses is still around 1530nm.

Hence, broadening the bandwidth of EDFAs to accommodate a larger number of WDM channels has become a subject of intense research. As an example of the state-of-the-art, a two-band architecture for an ultra-wideband EDFA with a record optical bandwidth of 80 nm has been demonstrated. To obtain a low noise figure and high output power, the two bands share a common first gain section and have distinct second gain sections. The 80nm bandwidth comes from one amplifier (so-called conventional band or C-band) from 1525.6 to 1562.5nm and another amplifier (so-called long band or L-band) from 1569.4 to 1612.8nm. As other examples, a 54nm gain bandwidth achieved with two EDFAs in a parallel configuration, i.e., one optimized for 1530-1560nm and the other optimized for 1576-1600 nm, and a 52nm EDFA that used two-stage EDFAs with an intermediate equalizer have been demonstrated.

These recent developments illustrate several points in the search for broader bandwidth amplifiers for the low-loss window in optical fibers. First, bandwidth in excess of 40-50nm require the use of parallel combination of amplifiers even with EDFAs. Second, the 80nm bandwidth may be very close to the theoretical maximum. The short wavelength side at about 1525nm is limited by the inherent absorption in erbium, and long wavelength side is limited by bend-induced losses in standard fibers at above 1620nm. Therefore, even with these recent advances, half of the bandwidth of the low-loss window, i.e., 1430-1530nm, remains without an optical amplifier.

There is a need for low noise Raman amplifiers and broadband transmission systems. There is a further need for distributed, discrete and hybrid amplifiers with improved noise figures. Another need exists for optical amplifiers suitable for wavelengths of 1480 nm or less, where the S^+ band is located.

SUMMARY OF THE INVENTION

Accordingly, an object of the present invention is to provide nonlinear polarization amplifiers.

Another object of the present invention is to provide a broadband fiber transmission system with at least one nonlinear polarization amplifier.

Yet another object of the present invention is to provide a broadband fiber

transmission system with reduced fiber non-linear impairments.

A further another object of the present invention is to provide a broadband fiber transmission system that operates over the full low loss window of available and optical fibers.

Another object of the present invention is to provide a broadband fiber transmission system that uses distributed Raman amplification to lower signal power requirements.

One or more of the objects of the present invention are achieved in a broadband amplifier. The broadband amplifier includes a transmission fiber, a splitter, an S+band distributed amplifier, a second optical amplifier, a combiner, and an output fiber. The splitter can be coupled to the transmission fiber. The splitter can split an optical signal into at least a first wavelength and a second wavelength. The S+ band distributed Raman amplifier can be coupled to the splitter that can operate in the range less than 1480 nm. A pump power of the S+ band distributed Raman amplifier can extend into the transmission fiber. The second optical amplifier can be coupled to the splitter. The combiner can be coupled to the S+ band distributed Raman amplifier and the second optical amplifier. The combiner can combine an optical signal into at least a first wavelength and a second wavelength. The output fiber can be coupled to the combiner.

In another embodiment of the invention, a method produces an amplified broadband optical signal in a transmission system. An optical signal is divided at a predetermined wavelength into a first beam having a wavelength less than the predetermined wavelength and a second beam having a wavelength greater than the predetermined wavelength. The first beam is directed to a transmission link in the transmission system that includes a distributed Raman amplifier operating in the wavelength range less than 1480 nm. The second beam is directed to a second amplifier. The first and second beams are combined to produce an amplified broadband optical signal.

In another embodiment of the invention, an S+band amplifier includes a distributed Raman amplifier, a WDM, a discrete amplifier, and a pump source. The distributed Raman amplifier can include a signal transmission line with at least a portion of the signal transmission line incorporating a distributed gain medium. The WDM can be coupled to the signal transmission line. The discrete amplifier canbe coupled to the WDM. The

pump source can be coupled to the WDM. The pump source can produce a pump beam λ_p at wavelengths less than 1400 nm.

In another embodiment of the invention, an S+ band amplifier includes a distributed Raman amplifier, a discrete amplifier, a WDM, and a pump source. The distributed Raman amplifier can include a signal transmission fiber with at least a portion of the signal transmission line incorporating a distributed gain medium. The discrete amplifier can be coupled to the transmission line. Additional gain can be generated from the distributed Raman amplifier to compensate for a higher loss in the fiber when the fiber experiences a transmission loss of 0.03 dB/km greater than the transmission loss in the fiber at 1550 nm. The WDM can be coupled to the signal transmission line. The WDM can be positioned between the distributed Raman amplifier and the discrete amplifier. The pump source can be coupled to the WDM. The pump source can produce a pump beam λ_p.

In another embodiment of the invention, a method produces an amplified broadband optical signal. At least one fiber is provided that has a low loss window of 1430 to 1620 nm and a distributed Raman amplifier coupled to the fiber. The distributed Raman amplifier is operated at wavelengths in the range less than 1480 nm. An amplified signal is generated at wavelengths less than 1480 nm.

In another embodiment of the invention, a method produces an amplified broadband optical signal. A distributed Raman amplifier is provided with at least one fiber that has a low loss window of 1430 to 1620 nm and a third order non-linearity amplifier coupled to the fiber. The third order non-linearity amplifier is operated at wavelengths in the range of less than 1480 nm. An amplified signal is generated at wavelengths less than 1480 nm.

In another embodiment of the invention a method produces an amplified broadband optical signal. A distributed Raman amplifier is provided with at least one fiber that has a low loss window of 1430 to 1620 nm and a third order non-linearity amplifier coupled to the fiber. The third order non-linearity amplifier is operated at wavelengths in the range of less than 1480 nm. An amplified signal is generated in the wavelength range of less than 1480 nm.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is a plot of loss verses wavelength for 50km fiber and the gain band of a typical EDFA.

Figure 2 is a graphical illustration of absorption and gain spectra of an EDFA.

Figure 3a is a graphical illustration of emission spectra of four EDFAs with different core compositions.

Figure 3b is a graphical illustration of absorption cross-section of erbium-doped glass of different compositions.

Figure 4 is a graphical illustration of a measured Raman-gain spectrum for fused silica at a pump wavelength of 1000nm.

Figure 5 is a graphical illustration that plots power gain coefficient 2g versus phase vector mismatch Δk for parametric amplification.

Figure 6 is a schematic diagram of one embodiment of a nonlinear polarization amplifier of the present invention.

Figure 7 is a graphical illustration of spectral broadening and gain expected from parametric amplification for a pump power of 1W and different separations between the pump and zero-dispersion wavelength.

Figure 8 is a graphical illustration of spectral broadening and gain expected from parametric amplification for a pump and zero-dispersion wavelength separation of 1nm and for varying pump powers.

Figure 9 is a schematic diagram of an embodiment of a broadband fiber transmission system of the present invention using an open-loop configuration.

Figure 10 is a schematic illustration of a broadband fiber transmission system of the present invention using a Sagnac Raman cavity that is pumped at 1240nm.

Figure 11 is a schematic illustration of an embodiment of a broadband fiber transmission system of the present invention using a Sagnac Raman cavity that is pumped at 1117nm.

Figure 12 is a schematic illustration of an embodiment of a broadband fiber transmission system of the present invention with two stages of nonlinear polarization amplifiers.

Figure 13 is a schematic illustration of an embodiment of a broadband fiber transmission system of the present invention that is a combination of an EDFA and a

nonlinear polarization amplifier.

Figure 14 is a graph of loss versus wavelengths comparing the wavelength range over which hybrid and discrete amplifiers can be operated.

Figure 15(a) is a schematic diagram of an embodiment of a multi-band amplifier module using a single WDM to split or combine the bands and distributed Raman amplification in the S+ band.

Figure 15(b) is a schematic diagram of an embodiment of a multi-band amplifier module using multiple WDM's to split or combine the bands and distributed Raman amplification in the S+ band.

Figure 16(a) is a schematic diagram of an embodiment of a multi-band amplifier module using a single WDM to split or combine the bands and hybrid amplification in the S+ band.

Figure 16(b) is a schematic diagram of an embodiment of a multi-band amplifier module of the present invention using multiple WDM's to split or combine the bands and hybrid amplification in the S+ band.

Figure 17 is a block chart of various embodiments of uses of amplifiers.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

Some embodiments provide a structure for exploiting almost the full 25THz of bandwidth available in the low-loss window of optical fibers from 1430nm to 1620nm. The broadband NLPA amplifier of some embodiments combines Raman amplification with either PA or 4WM to achieve bandwidth performance improvements that neither technology by itself has heretofore been able to deliver.

The broadband NLPA of other embodiments comprise an input port for inputting an optical signal having a wavelength λ, a distributed gain medium for receiving the optical signal and amplifying and spectrally broadening the same therein through nonlinear polarization, a pump source operated at wavelength λ_p for generating a pumping light to pump the distributed gain medium, and an output port for outputting the amplified and spectrally broadened optical signal. The distributed gain medium can have zero-dispersion at wavelength λ_0 such that $\lambda \geq \lambda_0 \geq \lambda_p$. The pumping light can cascade through the distributed gain medium a plurality of Raman orders including an intermediate order having a wavelength λ_r at a close proximity to the zero-dispersion wavelength λ_0 to phase

match four-wave mixing (if $\lambda_r < \lambda_0$) or parametric amplification (if $\lambda_r > \lambda_0$).

A first embodiment of the NLPA uses open-loop amplification with an optical fiber gain medium. A pump source operated at 1240nm can be used. The pump may be retro-reflected to increase the conversion efficiency. A second embodiment of the NLPA can use a Sagnac Raman cavity that is pumped at 1240nm. Feedback in the Sagnac Raman cavity can reduce the required pump power, and the broadband cavity design supports much of the generated bandwidth. Another embodiment of the NLPA can use a Sagnac Raman cavity pumped at 1117nm for a very broadband operation.

Other embodiments relate to a parallel optical amplification apparatus having a combination of optical amplifiers. In one embodiment, the parallel optical amplification apparatus comprises two parallel stages of NLPAs with one NLPA optimized for 1430 to 1480nm and the other for 1480 to 1530nm. In another embodiment, the full 25THz of the low-loss window in optical fibers can be exploited by a parallel combination of a Raman amplifier and a rare earth doped amplifier. In one embodiment, an NLPA can cover the low-loss window of approximately 1430nm to 1530nm, and an EDFA can cover the low-loss window of approximately 1530nm to 1620nm.

Stimulated Raman scattering effect, PA and 4WM can be result of third-order nonlinearities that occur when a dielectric material such as an optical fiber is exposed to intense light. The third-order nonlinear effect can be proportional to the instantaneous light intensity.

Stimulated Raman scattering can be an important nonlinear process that turns optical fibers into amplifiers and tunable lasers. Raman gain can result from the interaction of intense light with optical phonons in silica fibers, and Raman effect leads to a transfer of energy from one optical beam (the pump) to another optical beam (the signal). The signal can be downshifted in frequency (or upshifted in wavelength) by an amount determined by vibrational modes of silica fibers. The Raman gain coefficient g_r for the silica fibers is shown in Figure 4. Notably, the Raman gain g_r can extend over a large frequency range (up to 40 THz) with a broad peak centered at 13.2 THz (corresponding to a wavelength of 440 cm^{-1}). This behavior over the large frequency range can be due to the amorphous nature of the silica glass and enable the Raman effect to be used in broadband amplifiers. The Raman gain can depend on the composition of the fiber core and can vary with different dopant concentrations.

Raman amplification has some attractive features. First, Raman gain can upgrade existing fiber optic links because it is based on the interaction of pump light with optical phonons in the existing fibers. Second, in some embodiments there is no excessive loss in the absence of pump power - an important consideration for system reliability.

Raman cascading is the mechanism by which optical energy at the pump wavelength is transferred, through a series of nonlinear polarizations, to an optical signal at a longer wavelength. Each nonlinear polarization of the dielectric can produce a molecular vibrational state corresponding to a wavelength that is offset from the wavelength of the light that produced the stimulation. The nonlinear polarization effect can be distributed throughout the dielectric, resulting in a cascading series of wavelength shifts as energy at one wavelength excites a vibrational mode that produces light at a longer wavelength. This process can cascade through numerous orders. Because the Raman gain profile can have a peak centered at 13.2THz in silica fibers, one Raman order can be arranged to be separated from the previous order by 13.2THz.

Cascading makes stimulated Raman scattering amplifiers very desirable. Raman amplification can be used to amplify multiple wavelengths (as in wavelength division multiplexing) or short optical pulses because the gain spectrum can be very broad (a bandwidth of greater than 5THz around the peak at 13.2THz). Cascading can enable Raman amplification over a wide range of different wavelengths. By varying the pump wavelength or by using cascaded orders of Raman gain, the gain can be provided over the entire telecommunications window between 1300nm and 1600nm.

Parametric amplification and 4 wave mixing (PA/4WM) involve two pump (P) photons that create Stokes (S) and anti-Stokes (A) photons. Both PA/4WM and Raman amplification arise from the third order susceptibility $\chi^{(3)}$ in optical fibers. More specifically, the real part of $\chi^{(3)}$, the so-called nonlinear index of refraction n_2, is responsible for PA/4WM, while the imaginary part of $\chi^{(3)}$ associated with molecular vibrations corresponds to the Raman gain effect. In silica fibers of some embodiments, about 4/5ths of the n_2 is an electronic, instantaneous nonlinearity caused by ultraviolet resonances, while about 1/5th of n_2 arises from Raman-active vibrations, e.g., optical phonons. The imaginary part of this latter contribution corresponds to the Raman gain spectrum of Figure 4.

Whereas Raman amplification is attractive for providing optical gain, PA/4WM

can offer an efficient method to broaden the bandwidth of the optical gain. PA/4WM can have a much smaller frequency separation between pump and signal than Raman amplification, and the frequency difference may depend on the pump intensity. As in Raman amplification, one advantage of PA/4WM gain is that it can be present in every fiber. However, unlike the Raman effect, both PA and 4WM can require phase-matching. 4WM can be inefficient in long fibers due to the requirement for phase-matching. However, PA can act as self-phase-matched because the nonlinear index of refraction is used to phase match the pump and sidebands. This can be true in embodiments operating near the zero-dispersion wavelength in fibers. When 4WM and PA occur near the zero-dispersion wavelength of a single-mode fiber, phase-matching can become automatic in the fiber. In 4WM, sidebands can be generated without gain when the pump wavelength falls in the normal dispersion regime (where the pumping wavelength is shorter than the zero-dispersion wavelength). PA is 4-photon amplification in which the nonlinear index of refraction is used to phase match the pump and sidebands. For PA the pump wavelength can lie in the anomalous group velocity regime (i.e., where the pumping wavelength is longer than the zero-dispersion wavelength) and proper phase matching can require that pump and signal be co-propagating in some embodiments.

To illustrate the PA/4WM gain, the gain coefficient can be derived as:

$$g=\sqrt{(\gamma P)^2-\left[\left(\frac{\Delta\kappa}{2}\right)+\gamma P\right]^2} \qquad 1$$

The first term under the square root sign corresponds to the third order nonlinearity that couples the pump photons to the sidebands. The second term corresponds to the phase mismatch between the waves and it consists of two parts: one due to the wave-vector mismatch at the different wavelengths and the other due to the increase in nonlinear index induced by the pump. The nonlinearity parameter can be defined as

$$\gamma=\frac{\omega}{c}\frac{n_2}{A_{eff}}=\frac{2\pi}{\lambda}\frac{n_2}{A_{eff}} \qquad 2$$

Some embodiments operate near the zero-dispersion wavelength λ_0, and the propagation constant can be expanded as:

$$\Delta\kappa=-\frac{\lambda^2}{2\pi c}\left[\left.\frac{dD}{d\lambda}\right|_{\lambda_0}(\lambda_p-\lambda_0)\right]\Omega^2 \qquad 3$$

where

$$\Omega=\omega_p-\omega_s=\omega_a-\omega_p. \qquad 4$$

The pump wavelength can falls in the normal dispersion regime for some embodiments, and $D<0$, $\partial D/\partial\lambda>0$, $(\lambda_p-\lambda_0)<0$, so that $\Delta k>0$. In this case, g can be imaginary, and there may be no gain during the sideband generation process. This can correspond to the case of 4WM. Some embodiments operate in the anomalous group velocity dispersion regime, and $D>0$, $\partial D/\partial\lambda>0$, $(\lambda_p-\lambda_0)>0$, so that $\Delta k<0$. This can be the regime of PA, and the nonlinearity helps to reduce the phase mismatch (i.e., the two parts in the second term in Equation (1) are of opposite sign). There can be gain for PA, and the gain can be tunable with the pump power. For example, the power gain coefficient

2g is plotted schematically in Figure 5 for operation in the anomalous group velocity regime. The peak gain ($g_{peak}=\gamma P$) can occur at $\Delta k_{peak}=-2\gamma P$. The range over which the gain exists can be given by $0 > \Delta k > -4\gamma P$ in some embodiments. Thus, the peak gain can be proportional to the pump power, and the Δk range can be determined by the pump power. Consequently, from Equation (2) the bandwidth can be increased by increasing the pump power, increasing the nonlinear coefficient n_2 or decreasing the effective area A_{eff}. In other embodiments, for a given required frequency range over which gain is required, the pump requirements can be reduced by increasing the effective nonlinearity (n_2/A_{eff}).

Several embodiments lead to broadband gain for cascaded Raman amplification by arranging at least one intermediate Raman cascade order at close proximity to the zero-dispersion wavelength λ_0 (e.g., within ±5nm of λ_0 for some embodiments; within ±2nm for other embodiments). Either 4WM (if $\lambda_r < \lambda_0$) or PA (if $\lambda_r > \lambda_0$) can lead to spectral broadening of that particular Raman order. In subsequent Raman orders the bandwidth can grow even further. In other embodiments, the cascade Raman wavelength λ_r lies to the long wavelength side of λ_0 (i.e., in the anomalous dispersion regime), so that parametric amplification can occur.

An embodiment of the broadband NLPA is illustrated in Figure 6. Starting from the pump wavelength λ_p, cascaded Raman amplification can be used in the first few stages. The pump can be more than one Raman shift or 13.2THz away from the zero-dispersion wavelength. To keep higher efficiency in these initial steps, some embodiments can use a narrow band cavity design, such as designs based on gratings or wavelength selective couplers.

Some embodiments broaden the gain bandwidth by positioning one of the intermediate Raman cascade orders at a close proximity to the zero-dispersion wavelength λ_0. By operating close to λ_0, it can almost automatically phase-match either 4WM or PA. In the subsequent cascaded Raman orders, the gain bandwidth may continue to broaden. This occurs because the effective gain bandwidth of Raman is the convolution of the bandwidth of the pump (in this case, the previous Raman cascade order) with the Raman gain curve. In some embodiments with Raman amplification, the gain spectrum follows the pump spectrum. As the pump wavelength changes, the Raman gain can change as well, separated by the distance of optical phonon energy which in silica fibers is an

approximately 13.2THz down-shift in frequency.

If the fiber is conventional so-called standard fiber, then zero-dispersion wavelength λ_0 can be about 1310nm. For dispersion-shifted fiber, the zero-dispersion wavelength λ_0 can shift to longer wavelengths by adding waveguide dispersion. In other embodiments, a dispersion-flattened fiber can be used for low dispersion values over one or more of the Raman cascade orders. In some embodiments with dispersion-flattened fiber, the dispersion slope can be small, so the gain bandwidth can be even larger (c.f. Equations (1) and (3)).

The Raman gain spectrum can follow the pump spectrum, such as when there is nothing in the Raman cavity to restrict the bandwidth of the subsequent orders. For these higher cascade order Raman laser schemes, some embodiments use gratings or wavelength selective couplers. Other embodiments with the broadband cavity design of the Sagnac Raman amplifier and laser can have increased bandwidth with a tailored pump spectrum. A single-pass fiber design can constitute the broadest bandwidth design. A broadband cavity such as the Sagnac Raman cavity can have the feedback used to lower the threshold and the required pump power. Broadening the bandwidth can lead to a drop in efficiency, so the pump powers can be higher for the broadband cavity designs.

Cascaded Raman amplification can reach the 1430-1530nm range of the low-loss window. Pumping can occur with a commercially available cladding-pumped fiber laser, which operates around 1060 to 1140nm. The various Raman orders, each separated by 13.2Thz from the previous order, are set forth in Table 1.

Table 1. Various Raman orders when pumping between 1060 and 1140nm (separation of 13.2THz between orders)

Wavelength (nm)	$\Delta\lambda$	Wavelength (nm)	$\Delta\lambda$
1060.00	51.86	1110.00	57.00
1111.86	57.19	1167.00	63.17
1169.05	63.39	1230.16	70.40
1232.44	70.66	1300.56	78.94
1303.11	79.26	1379.50	89.14
1382.37	89.53	1468.64	101.46
1471.90	101.93	1570.10	116.52
1573.82	117.09	1686.62	135.20

Wavelength (nm)	$\Delta\lambda$	Wavelength (nm)	$\Delta\lambda$
1070.00	52.86	1117.00	57.74
1122.86	58.36	1174.74	64.03

1181.22	64.76	1238.77	71.41
1245.98	72.27	1310.18	80.15
1318.25	81.17	1390.33	90.59
1399.42	91.82	1480.92	103.22
1491.25	104.72	1584.15	118.69
1595.97	120.54	1702.84	137.92

Wavelength (nm)	Δλ	Wavelength (nm)	Δλ
1080.00	53.88	1120.00	58.05
1133.88	59.54	1178.05	64.40
1193.42	66.14	1242.46	71.85
1259.56	73.90	1314.31	80.67
1333.47	83.11	1394.98	91.22
1416.58	94.16	1486.20	103.99
1510.74	107.57	1590.19	119.63
1618.32	124.07	1709.82	139.10

Wavelength (nm)	Δλ	Wavelength (nm)	Δλ
1090.00	54.91	1130.00	59.12
1144.91	60.74	1189.12	65.65
1205.65	67.54	1254.77	73.32
1273.19	75.56	1328.10	82.43
1348.74	85.09	1410.53	93.33
1433.83	96.55	1503.86	106.56
1530.38	110.49	1610.42	122.81
1640.87	127.69	1733.24	143.09

Wavelength (nm)	Δλ	Wavelength (nm)	Δλ
1100.00	55.95	1140.00	60.20
1155.95	61.94	1200.20	66.92
1217.89	68.96	1267.12	74.82
1286.85	77.24	1341.93	84.21
1364.09	87.10	1426.14	95.48
1451.19	98.98	1521.62	109.18
1550.17	113.47	1630.81	126.07
1663.64	131.40	1756.87	147.19

To obtain gain between 1430nm and 1520nm, the pump can be operated between 1090nm and 1140nm, and five cascaded Raman orders can be used to reach the desired wavelength. To make use of the broadening from PA or 4WM, a pumping scheme can be selected in the middle of this range, i.e., starting with a pump wavelength of 1117nm. Then, the various Raman orders land at approximately 1175nm, 1240nm, 1310nm, 1390nm and finally 1480nm. In particular, the third Raman frequency (1310nm) passes through the zero-dispersion point of a standard fiber, and the next order (1390nm) can be close if the fiber is dispersion shifted. A broadband gain can be expected for wavelengths

in the 1430-1530nm range centered around 1480nm by using a fiber with a standard dispersion and a pump wavelength of 1117nm, 1175nm or 1240nm.

Broadening can be expected from PA. A standard fiber can be used and the pump wavelength can start at 1117nm. The calculations use Equations (1-4) with the following typical parameters for high-Raman cross-section fiber in some embodiments: λ_0 = 1310nm, $\gamma = 9.9W^{-1}km^{-1}$, and a dispersion slope of 0.05ps/nm-km. In Figure 7, the gain coefficient for PA is plotted versus wavelength at a pump power of 1W and wavelength separations (λ_r-λ_0) of 0.5, 1, 2 and 5nm. For a wavelength separation of 2nm, the PA peak gain occurs at ±10nm, so the spectral broadening is over 20nm. The closer the pump wavelength approaches the zero-dispersion wavelength, the wider the gain bandwidth can be. In addition, Figure 8 plots the gain versus wavelength for a separation of (λ_r-λ_0)=1nm and pump powers of 0.7, 1, 2, and 3W. The peak gain can increase directly proportionally to the pump power, while the bandwidth can increase as the square root of pump power.

Figure 9 shows a first embodiment which uses an open-loop design to produce an amplified broadband signal for a range of wavelengths between 1430nm and 1530nm. The open-loop design is a nonlinear polarization amplifier, and may have a high pump power requirement. In the NLPA amplifier 20 as illustrated in Figure 9, an optical signal having a wavelength between 1430nm and 1530nm is input from an input port 25 to an optical fiber 30. The optical fiber 30 is pumped by a pumping light generated by a pumping laser 35 operated at a wavelength of about 1240nm. The optical signal is amplified and spectrally broadened in the fiber by nonlinear polarization, and output through an output port 40. The configuration is so arranged that the optical signal can have a wavelength greater than the zero-dispersion wavelength of the fiber, which in turn is greater than the pumping wavelength of 1240nm.

In this open-loop configuration, the fiber can have a cut-off wavelength below 1240nm to be single-mode (spatial) over all wavelengths of the Raman cascade. Three choices of the fiber embodiments can be used in some embodiments. First, a standard dispersion fiber with a zero-dispersion wavelength at about 1310nm. Second, two fibers spliced together with one fiber having a zero-dispersion wavelength at about 1310nm (first cascade) and the other at 1390nm (second cascade). Third, a dispersion-flattened fiber with low-dispersion at least between 1310nm and 1390nm. The reduced dispersion slope of such a dispersion-flattened fiber increases significantly the bandwidth for PA or 4WM.

Exemplary 1240nm pump lasers include: (a) an 1117nm cladding-pumped fiber laser followed by a coupler-based or grating-based Raman oscillator cavity (with gratings for 1117nm, 1175nm and 1240nm); (b) an optically-pumped semiconductor laser; or (c) a chromium-doped forsterite laser. At one end of the fiber, a 1240nm retro-reflector 45 can be placed to increase pumping conversion efficiency. The retro-reflector can be a dichroic mirror or a 1240nm grating. The input and output ports can be WDM couplers, and isolators can be used at the input and output ports to prevent lasing due to spurious feedback. A counter-propagating geometry can average out noise fluctuations in this open-loop configuration. A co-propagating geometry can be used.

To reduce the pump power requirements, a broadband cavity such as the Sagnac Raman cavity can be used in some embodiments. Figure 10 illustrates an embodiment of the NLPA that uses a Sagnac Raman cavity design with a 1240nm pump. Referring to Figure 10, the Sagnac Raman cavity of the NLPA 60 can be formed by a broadband mirror 70 and a loop mirror comprising a Raman gain fiber 65 and an optical coupler 90 connected thereto. An optical signal can have a wavelength between 1430nm to 1530nm input through an input port 75 to the Raman gain fiber 65. A pumping laser 80 can operate at a wavelength 1240nm and generate a pumping light that pumps the fiber 65 through a coupler 85. The optical signal can be amplified and spectrally broadened in the fiber by nonlinear polarization, and output through an output port 95. The configuration can be arranged so that the optical signal has a wavelength greater than the zero-dispersion wavelength of the fiber, which in turn can be greater than the pumping wavelength of 1240nm.

The Raman gain fiber can have the same characteristics as described above for the open-loop design. Similarly, the pumping lasers used in the first embodiment can be used in this second embodiment. The broadband NLPA may further include a polarization controller 100 in the Sagnac Raman cavity for controlling polarization state. In other embodiments, if the fiber is polarization maintained, the polarization controller can be unnecessary. The optical coupler 90 is nominally 50:50 at least for the optical signal having a wavelength between about 1240nm and 1430nm. The coupler 85 can be a WDM coupler which transmits at least at a wavelength between about 1300nm and 1430nm. The input port and output port each comprises a WDM coupler which can transmit at least at a wavelength between about 1240nm and 1425nm. One embodiment of the Sagnac Raman

cavity has a passive noise dampening property that leads to quieter cascading of various Raman orders.

In various embodiments, a Sagnac Raman cavity can be used for all five Raman cascade orders between 1117nm and the low-loss window. Figure 11 illustrates a third embodiment of a five-order Sagnac Raman amplifier for NLPA operation. A cladding-pumped fiber laser operating around 1117nm can be used as a pumping laser 120. Different fiber combinations embodiment can be used. The fibers can have a cut-off wavelength below 1117nm to accommodate single-mode operation for the pump. An optical coupler 130 can be nominally 50:50 at least for the optical signal having the wavelength between about 1117nm and 1430nm. A coupler 125 can be a WDM coupler which transmits at least at wavelengths between about 1165nm and 1430nm. Moreover, the input and output ports each comprises a WDM coupler which can transmit at least at wavelengths between about 1117nm and 1425nm. Although the wavelength range of the various components increases, this configuration can lead to an even broader gain band since the pump bandwidth is allowed to increase even during the first two cascades between 1117nm and 1240nm for some embodiments. Also, the noise dampening property of the Sagnac cavity can be used over all five Raman orders for some embodiments.

Some embodiments include an NLPA. An optical signal having a wavelength λ is input through an input port into a distributed gain medium having zero-dispersion at a wavelength λ_0, such as an optical fiber, which can be pumped by a pumping light from a pump source operated at a wavelength λ_p, wherein $\lambda \geq \lambda_0 \geq \lambda_p$. The pumping light can cascade through the distributed gain medium a plurality of Raman orders including an intermediate order having a wavelength λ_r at a close proximity to the zero-dispersion wavelength λ_0 to phase match four-wave mixing (if $\lambda_r < \lambda_0$) or parametric amplification (if $\lambda_r > \lambda_0$). The amplified and spectrally broadened optical signal is output through an output port.

The above embodiments demonstrate that a single NLPA can accommodate the full bandwidth of the low-loss window. Moreover, the full bandwidth of the low-loss window may be reached by using a parallel optical amplification apparatus having a combination of two or more Raman amplifiers and rare earth doped amplifiers. In some embodiments, the NLPAs and EDFAs are used.

Figure 12 shows a first embodiment of the parallel optical amplification apparatus using a combination of two NLPAs for a range of wavelengths between 1430nm and 1530nm. Referring to Figure 12, a divider 170 divides an optical signal having a wavelength between 1430nm to 1530nm at a predetermined wavelength, such as 1480nm, into a first beam having a wavelength less than the predetermined wavelength and a second beam having a wavelength greater than the predetermined wavelength in some embodiments. The first beam is input into a first NLPA 180 for amplification and spectral broadening therein. The second beam is input into a second NLPA 190 for amplification and spectral broadening therein. Outputs from the first and second NLPAs can be combined by a combiner 200 to produce an amplified and spectrally broadened optical signal. The input port 170 and output port 200 can be preferably WDM couplers in some embodiments.

In other embodiments the first NLPA 180 can be optimized for 1430-1480nm and centered at 1455nm, while the second NLPA can be optimized for 1480-1530nm and centered at 1505nm. From Table 1, these two windows can be achieved in a five-order cascade by starting with a pump wavelength of about 1100nm for the short-wavelength side and a pump wavelength of about 1130nm for the long-wavelength side. For the short-wavelength side, the fiber can have a zero-dispersion around 1365nm, while for the long-wavelength side, the fiber zero-dispersion can be around 1328nm or 1410nm.

The narrower-bandwidth for each NLPA can lead to an increased efficiency for each amplifier in some embodiments. Furthermore, the components may be more easily manufactured, since the wavelength window is not as large. The multiple amplifiers in some embodiments may allow for gradual upgrades of systems, adding bandwidth to the EDFA window as needed.

A spectrum of 1430-1620nm in the low-loss window can be amplified and spectrally broadened by using a parallel optical amplification apparatus comprising Raman amplifiers and rare earth doped amplifiers. Figure 13 describes a second embodiment of the parallel optical amplification apparatus. The amplification apparatus comprises a broadband NLPA 240 and a EDFA 250. A divider 230 of the apparatus divides an optical signal having a wavelength between 1430nm and 1620nm at a predetermined wavelength, preferably at 1525nm, into a first beam having a wavelength less than the predetermined wavelength and a second beam having a wavelength greater than the predetermined

wavelength in some embodiments. The broadband NLPA 240 receives the first beam and produces an amplified broadband first beam. The EDFA 250 receives the second beam and produces an amplified broadband second beam. A combiner 260 combines the amplified and spectrally broadened first and second beams to produce an amplified broadband optical signal. Other embodiments can have WDM couplers for the divider 230 and the combiner 260.

To use some embodiments with multi-wavelength WDM channels, at the output of the amplifier, gain can be equalized. This wavelength dependency or nonuniformity of the gain band can have little impact on single-channel transmission. However, it can render the amplifier unsuitable for multichannel operation through a cascade of amplifiers. As channels at different wavelengths propagate through a chain of amplifiers, they can accumulate increasing discrepancies between them in terms of gain and signal-to-noise ratio. Using gain-flattening elements can significantly increase the usable bandwidth of a long chain of amplifiers. For example, the NLPA can be followed by a gain flattening element to provide gain equalization for different channels in some embodiments. Alternately, the gain flattening element could be introduced directly into the Sagnac interferometer loop in other embodiments, such as in Figs. 10 or 11.

The wavelength range where hybrid amplifiers with DRA's are to be used, can be considered to facilitate future upgrades in bandwidth. DRA's used in the C-band (1530-1565nm) or L-band (1570-1610nm) can restrict opening up the S-band (1480-1530nm) or S^+ band (1430-1480nm). DRA's can use pump bands that are 13.2THz, or about 100nm, shorter in wavelength than the signal band. For the C- or L-bands, DRA's can have pumps that lie in the wavelength range between 1430-1510nm. The pump bands can be at a shorter wavelength than any signal band. The pump might deplete energy from the signal channels through the Raman process.

In embodiments where fiber bandwidth exceeds 100nm, DRA can be inconsistent with further band expansion. For example, DRA's for C- and L-bands can prevent using the S- and S^+-bands in the fiber in some embodiments. The pumps for DRA can lie at shorter wavelength than any signal band. To maximize the capacity of the fiber in some embodiments DRA's can be used at the shortest bands to be used in the fiber.

DRA's can be useful when the fiber loss increases in some embodiments. For example, when the fiber loss increases >0.03dB/km from the minimum loss (i.e., for an

80km link that would mean an additional loss of 2.4dB), then the span design can be more difficult in some embodiments. The higher loss means that higher gain can be used for a fixed amplifier spacing, which can mean that more noise can be introduced. In turn, this can mean that the signal power can be increased or the bit-rate reduced to maintain the overall SNR. If hybrid amplifiers can be used in these higher loss windows, the improved NF can be used to offset the drawbacks from the higher loss.

Figure 14 shows the loss coefficient (in dB/km) for three generations of fibers. The loss above 1600 nm can be due to infrared absorption, while the gradual increase in loss below 1550nm can be due to Rayleigh scattering. The peak near 1390nm can result from water absorption of OH bonds. With some newer fibers, the fibers can be dried better, so the water peak can be reduced. Also represented in Figure 14 are different bands. The C- and L-bands can stretch from approximately 1530-1610nm, the S-band from 1480-1530nm, and the S^+ band from 1430-1480nm.

For some embodiments of fiber types, the loss in the S-band can be lower or equal to the loss in the C- and L-bands. Since these three bands can be the lowest loss bands, discrete amplifiers can be used in these bands in some embodiments. For example, the C- and L-bands can use discrete EDFA's, while the S-band can use Raman amplifiers.

In the S^+ band and shorter (i.e., wavelengths shorter than 1480nm), the loss can rise above the loss in the C- and L-bands due to Rayleigh scattering and the water absorption. The S^+ band and shorter wavelengths can advantageously use DRA's in some embodiments. Since these bands can be on the shortest wavelength side, DRA's may not block further expansion of the bands in some embodiments. The loss in the shorter wavelengths can be too high for these wavelengths to be used in long-haul communications in some embodiments. Also, for some embodiments with DRA's used in the wavelength range just beyond the water absorption peak (i.e., wavelengths between 1430-1480nm), the pumps can be at wavelengths approximately 1340-1380nm, just below the water peak.

Figures 15(a), 15(b), 16(a) and 16(b) illustrate various embodiments with an amplifier module incorporated into a broadband transmission system that operates in multiple wavelength bands. Discrete amplifiers can be used in the C, L, S bands, and combinations thereof. A distributed Raman amplifier or hybrid amplifier can be used for the S+ band.

In Figures 15(a) and 15(b) a pump is introduced in parallel with these discrete amplifiers to implement various embodiments of a distributed Raman amplifier in the S+ band. In Figure 15(a) a single WDM is used to split up the multiple bands while in Figure 15(b) a serial combination of WDM's is used to split and combine the bands.

In Figures 16(a) and 16(b) a pump is introduced in parallel with these discrete amplifiers to implement embodiments of a hybrid Raman amplifier in the S+ band. In Figure 16(a) a single WDM is used to split up the multiple bands while in Figure 16(b) a serial combination of WDM's is used to split and combine the bands.

In another embodiment, a broadband fiber transmission system is provided with low noise hybrid optical amplifiers to compensate for loss at wavelength of 1480 nm or less or that have a fiber loss of 0.03 dB/km or more above the minimum loss of the fiber. One embodiment provides a broadband fiber transmission system with low noise distributed optical amplifiers to compensate for loss at wavelength of 1480 nm or less or that have a fiber loss of 0.03 dB/km or more above the minimum loss of the fiber. Additionally, another embodiment is a broadband fiber transmission system with low noise discrete optical amplifiers to compensate for loss at wavelength of 1480 nm or less or that have a fiber loss of 0.03 dB/km or more above the minimum loss of the fiber. A further embodiment is a broadband fiber transmission system with low noise hybrid optical amplifiers to compensate for loss at wavelengths of 1400 to 1480 nm.

DRA's can improve the NF of an optical amplifier in some embodiments. For maximum fiber capacity, hybrid amplifiers can be used in the shortest wavelength bands in some embodiments, where the fiber loss is rising. For example, at wavelengths shorter than 1480nm where the loss is at least 0.03dB/km higher than at the loss minimum, hybrid amplifiers can be valuable. Discrete amplifiers in the C-, L- and S-bands and hybrid amplifiers in the S+ or shorter wavelength bands, can expand the fiber bandwidth beyond 120nm.

One embodiment of a method of producing an amplified broadband optical signal in a transmission system comprises dividing an optical signal at a predetermined wavelength into a first beam having a wavelength less than the predetermined wavelength and a second beam having a wavelength greater than the predetermined wavelength; directing the first beam to a transmission link in the transmission system that includes a distributed Raman amplifier operating in the wavelength range less than 1480 nm;

directing the second beam to a second amplifier; and combining the first and second beams to produce an amplified broadband optical signal. The second amplifier can be a Raman amplifier, a rare earth doped fiber amplifier, a thulium doped fiber amplifier, and/or an erbium doped fiber amplifier.

One embodiment of a broadband amplifier comprises a transmission fiber, a splitter, an S+ band distributed amplifier, a second optical amplifier, a combiner, and an output fiber. The splitter can be coupled to the transmission fiber. The splitter can split an optical signal into at least a first wavelength and a second wavelength. The splitter can direct the first wavelength to the S+ band distributed Raman amplifier. The splitter can direct the second wavelength to the second optical amplifier. The S+ band distributed Raman amplifier can be coupled to the splitter. The splitter can operate in the range less than 1480 nm. A pump power of the S+ band distributed Raman amplifier can extend into the transmission fiber. The S+ band distributed Raman amplifier can be a portion of the transmission fiber. The transmission fiber can incorporate a distributed gain medium. The second optical amplifier can be coupled to the splitter. The combiner can be coupled to the S+ band distributed Raman amplifier and/or the second optical amplifier. The combiner can combine an optical signal into at least a first wavelength and a second wavelength. The output fiber can be coupled to the combiner.

One embodiment of an S+band amplifier comprises a distributed Raman amplifier, a WDM, a discrete amplifier, and a pump source. The distributed Raman amplifier can include a signal transmission line. At least a portion of the signal transmission line can incorporate a distributed gain medium. The WDM can be coupled to the signal transmission line. The discrete amplifier can be coupled to the WDM. The pump source can be coupled to the WDM. The pump source can produce a pump beam λ_p at wavelengths less than 1400 nm. The distributed Raman amplifier can be a low noise pre-amplifier for the discrete amplifier.

One embodiment of an S+band amplifier comprises a distributed Raman amplifier, a discrete amplifier, a WDM, and a pump source. The distributed Raman amplifier can include a signal transmission fiber. At least a portion of the signal transmission line can incorporate a distributed gain medium. The discrete amplifier can be coupled to the transmission line. Additional gain can be generated from the distributed Raman amplifier to compensate for a higher loss in the fiber when the fiber experiences a transmission loss

of 0.03 dB/km greater than the transmission loss in the fiber at 1550 nm. The additional gain can be generated without adding a proportional amount of noise in the system. The WDM can be coupled to the signal transmission line. The WDM can be positioned between the distributed Raman amplifier and the discrete amplifier. The pump source can be coupled to the WDM. The pump source can produce a pump beam λ_p, which can be at wavelengths less than 1400 nm.

One embodiment of a method of producing an amplified broadband optical signal comprises providing at least one fiber that has a low loss window of 1430 to 1620 nm and a distributed Raman amplifier coupled to the fiber; operating the distributed Raman amplifier at wavelengths in the range less than 1480 nm; and generating an amplified signal at wavelengths less than 1480 nm. The low loss can be at least 2 dB/km, or at least 1 dB/km. The distributed Raman amplifier can be coupled to a discrete optical amplifier. The distributed Raman can be a low noise pre-amplifier for the discrete optical amplifier. The distributed Raman amplifier can have a pump power that extends into a transmission line fiber. The discrete optical amplifier can be a Raman amplifier, a rare earth doped amplifier, an erbium doped fiber amplifier, and/or a thulium doped fiber amplifier.

One embodiment of a method of producing an amplified broadband optical signal comprises providing a distributed Raman amplifier with at least one fiber that has a low loss window of 1430 to 1620 nm and a third order non-linearity amplifier coupled to the fiber; operating the third order non-linearity amplifier at wavelengths in the range of less than 1480 nm; and generating an amplified signal at wavelengths less than 1480 nm. The low loss can be at least 2 dB/km, or at least 1 dB/km. The distributed Raman amplifier can be coupled to a discrete optical amplifier. The discrete optical amplifier can be a Raman amplifier, a rare-earth doped amplifier, an erbium doped fiber amplifier, and/or a thulium doped fiber amplifier.

One embodiment of a method of producing an amplified broadband optical signal comprises providing a distributed Raman amplifier with at least one fiber that has a low loss window of 1430 to 1620 nm and a third order non-linearity amplifier coupled to the fiber; operating the third order non-linearity amplifier at wavelengths in the range of less than 1480 nm; and generating an amplified signal in the wavelength range of less than 1480 nm. The third order non-linearity amplifier can be operated in a transmission system that uses at least 80 nm of bandwidth.

It is understood that various other modifications will be readily apparent to those skilled in the art without departing from the scope and spirit of the invention. Accordingly, it is not intended that the scope of the claims appended hereto be limited to the description set forth herein, but rather that the claims be construed as encompassing all the features of the patentable novelty that reside in the present invention, including all features that would be treated as equivalents thereof by those skilled in the art to which this invention pertains.

WHAT IS CLAIMED IS:

1. A method of producing an amplified broadband optical signal in a transmission system, comprising:

dividing an optical signal at a predetermined wavelength into a first beam having a wavelength less than the predetermined wavelength and a second beam having a wavelength greater than the predetermined wavelength;

directing the first beam to a transmission link in the transmission system that includes a distributed Raman amplifier operating in the wavelength range less than 1480 nm;

directing the second beam to a second amplifier; and

combining the first and second beams to produce an amplified broadband optical signal.

2. The method of claim 1, wherein the second amplifier is a Raman amplifier.

3. The method of claim 1, wherein the second amplifier is a rare earth doped fiber amplifier.

4. The method of claim 1, wherein the second amplifier is a thulium doped fiber amplifier.

5. The method of claim 1, wherein the second amplifier is an erbium doped fiber amplifier.

6. A broadband amplifier, comprising:

a transmission fiber;

a splitter coupled to the transmission fiber, the splitter splitting an optical signal into at least a first wavelength and a second wavelength;

an S+ band distributed Raman amplifier coupled to the splitter that operates in the range less than 1480 nm, wherein a pump power of the S+ band distributed Raman amplifier extends into the transmission fiber;

a second optical amplifier coupled to the splitter;

a combiner coupled to the S+ band distributed Raman amplifier and the second optical amplifier, the combiner combining an optical signal into at least a first wavelength and a second wavelength; and

an output fiber coupled to the combiner.

7 The amplifier of claim 6, wherein the S+ band distributed Raman amplifier is a portion of the transmission fiber that incorporates therein a distributed gain medium.

8. The amplifier of claim 6, wherein the splitter directs the first wavelength to the S+ band distributed Raman amplifier and the second wavelength to the second optical amplifier.

9. An S+band amplifier, comprising:

a distributed Raman amplifier that includes a signal transmission line with at least a portion of the signal transmission line incorporating a distributed gain medium;

a WDM coupled to the signal transmission line;

a discrete amplifier coupled to the WDM; and

a pump source coupled to the WDM and producing a pump beam λ_p at wavelengths less than 1400 nm.

10. The amplifier of claim 9, wherein the distributed Raman amplifier is a low noise pre-amplifier for the discrete amplifier.

11. An S+band amplifier, comprising:

a distributed Raman amplifier that includes a signal transmission fiber with at least a portion of the signal transmission line incorporating a distributed gain medium;

a discrete amplifier coupled to the transmission line, wherein additional gain is generated from the distributed Raman amplifier to compensate for a higher loss in the fiber when the fiber experiences a transmission loss of 0.03 dB/km greater than the transmission loss in the fiber at 1550 nm.; and

a WDM coupled to the signal transmission line and positioned between the distributed Raman amplifier and the discrete amplifier; and

a pump source coupled to the WDM and producing a pump beam λ_p.

12. The amplifier of claim 11, wherein the additional gain is generated without adding a proportional amount of noise in the system.

13. The amplifier of claim 11, wherein the pump beam λ_p is at wavelengths less than 1400 nm.

14. A method of producing an amplified broadband optical signal comprising:

providing at least one fiber that has a low loss window of 1430 to 1620 nm and a distributed Raman amplifier coupled to the fiber;

operating the distributed Raman amplifier at wavelengths in the range less than 1480 nm; and

generating an amplified signal at wavelengths less than 1480 nm.

15. The method of claim 14, wherein the low loss is at least 2 dB/km.

16. The method of claim 14, wherein the low loss is at least 1 dB/km.

17. The method of claim 14, wherein the distributed Raman amplifier is coupled to a discrete optical amplifier.

18. The method of claim 14, wherein the distributed Raman is a low noise pre-amplifier for the discrete optical amplifier.

19. The method of claim 14, wherein the distributed Raman amplifier has a pump power that extends into a transmission line fiber.

20. The method of claim 17, wherein the discrete optical amplifier is a Raman amplifier.

21. The method of claim 17, wherein the discrete optical amplifier is a rare earth doped amplifier.

22. The method of claim 17, wherein the discrete optical amplifier is an erbium doped fiber amplifier.

23. The method of claim 17, wherein the discrete optical amplifier is a thulium doped fiber amplifier.

24. A method of producing an amplified broadband optical signal comprising:

providing a distributed Raman amplifier with at least one fiber that has a low loss window of 1430 to 1620 nm and a third order non-linearity amplifier coupled to the fiber;

operating the third order non-linearity amplifier at wavelengths in the range of less than 1480 nm; and

generating an amplified signal at wavelengths less than 1480 nm.

25. The method of claim 24, wherein the low loss is at least 2 dB/km.

26. The method of claim 24, wherein the low loss is at least 1 dB/km.

27. The method of claim 24, wherein the distributed Raman amplifier is coupled to a discrete optical amplifier.

28. The method of claim 27, wherein the discrete optical amplifier is a Raman amplifier.

29. The method of claim 27, wherein the discrete optical amplifier is a rare-earth doped amplifier.

30. The method of claim 27, wherein the discrete optical amplifier is an erbium doped fiber amplifier.

31. The method of claim 27, wherein the discrete optical amplifier is a thulium doped fiber amplifier.

32. A method of producing an amplified broadband optical signal comprising:

providing a distributed Raman amplifier with at least one fiber that has a low loss window of 1430 to 1620 nm and a third order non-linearity amplifier coupled to the fiber;

operating the third order non-linearity amplifier at wavelengths in the range of less than 1480 nm; and

generating an amplified signal in the wavelength range of less than 1480 nm.

33. The method of claim 32, wherein the third order non-linearity amplifier is operated in a transmission system that uses at least 80 nm of bandwidth.

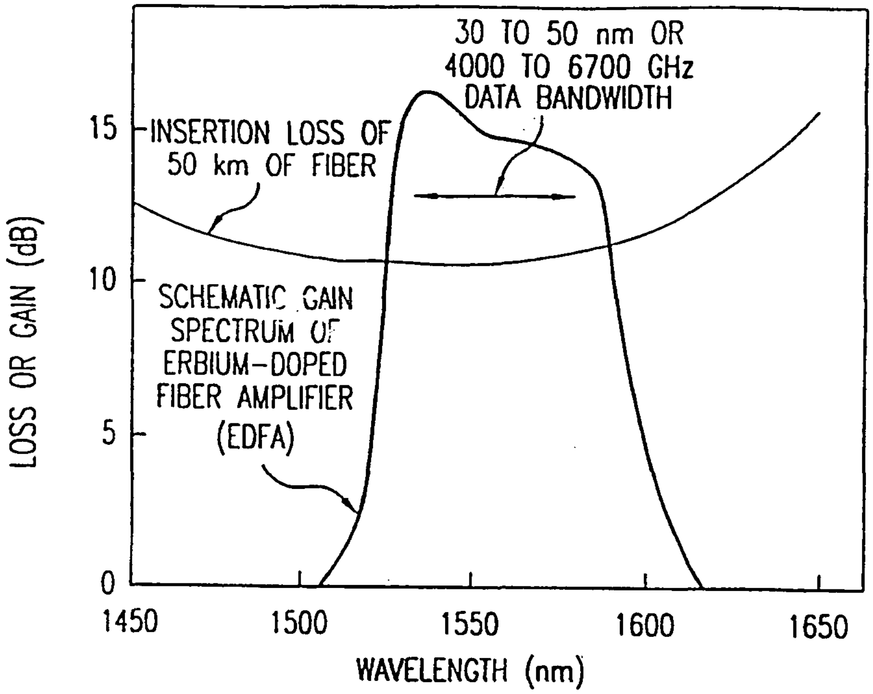

FIG.1
PRIOR ART

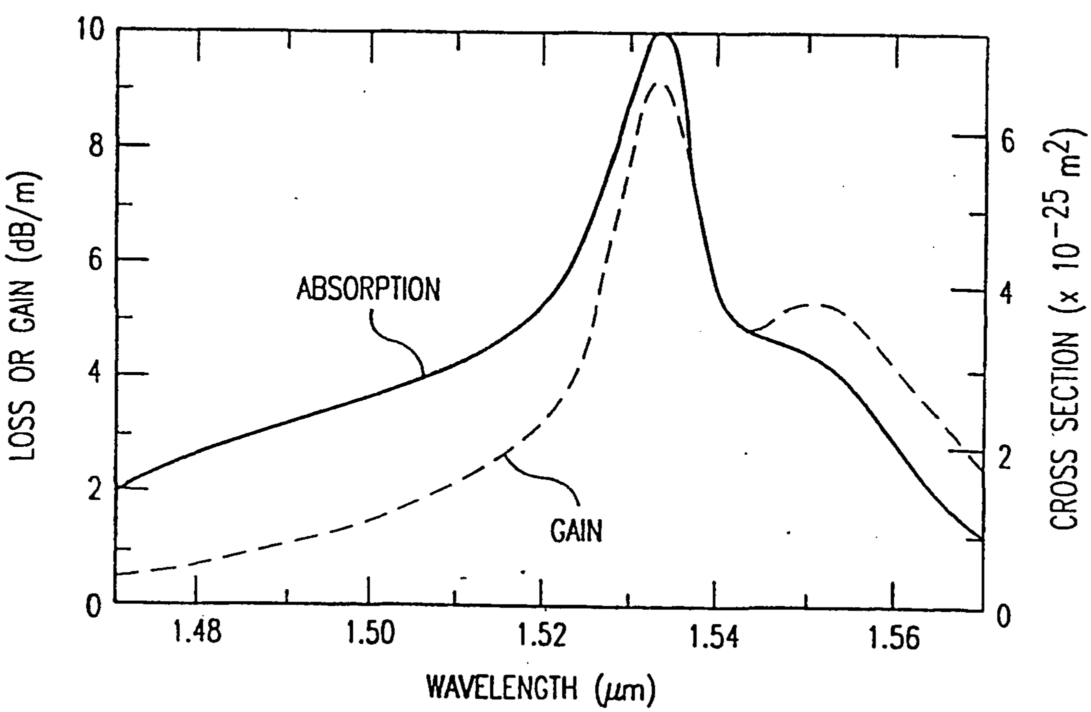

FIG.2
PRIOR ART

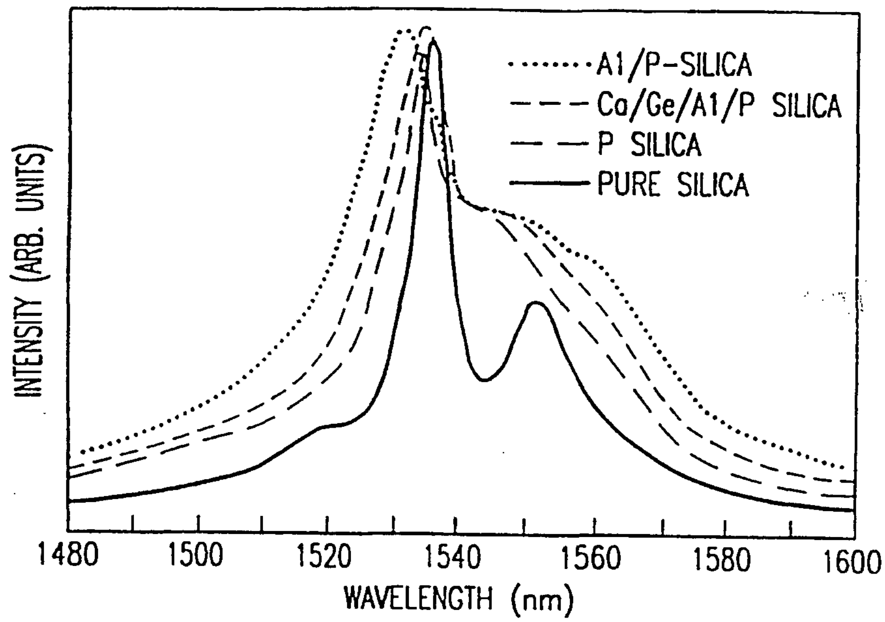

FIG.3a
PRIOR ART

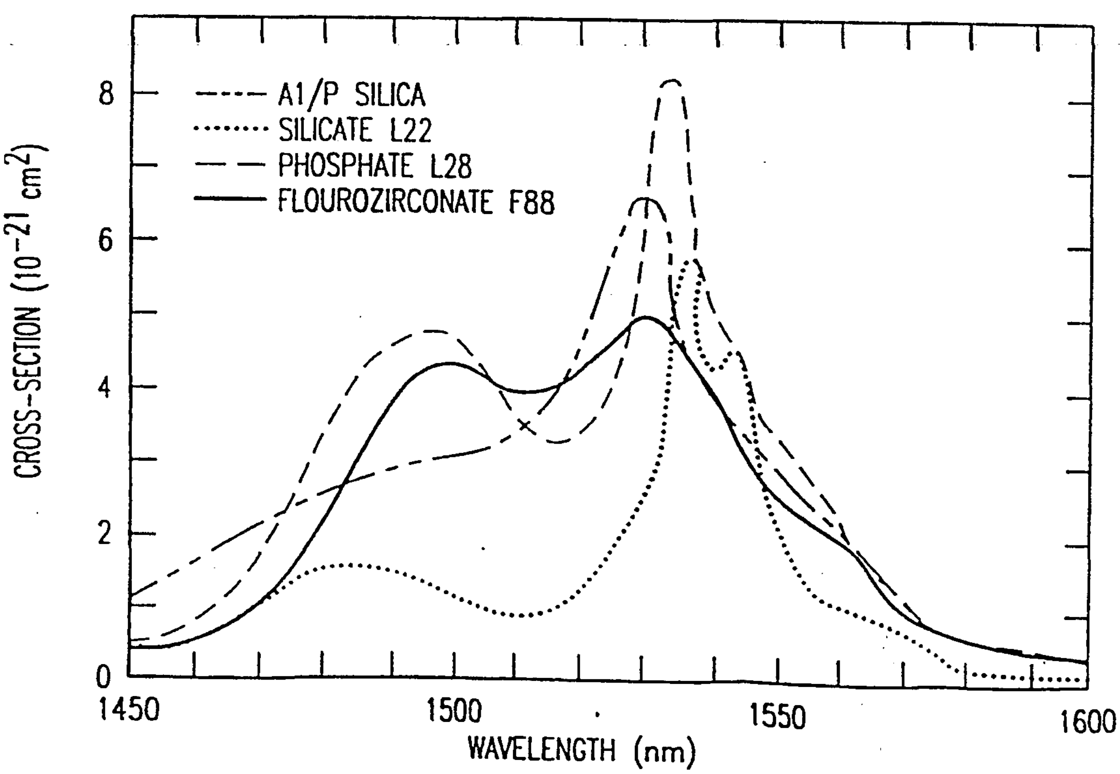

FIG.3b
PRIOR ART

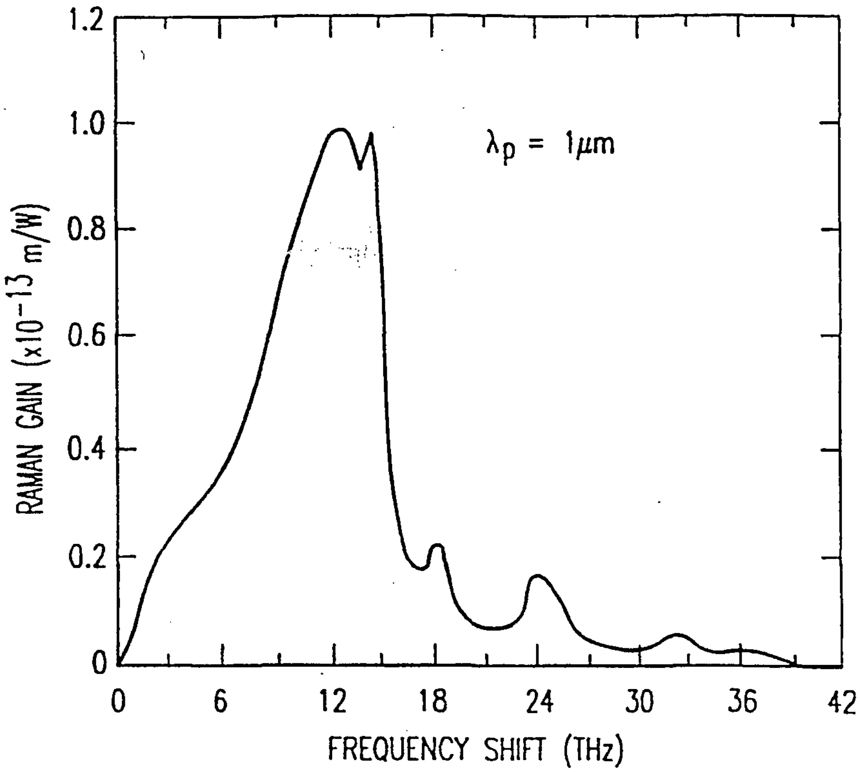

FIG.4
PRIOR ART

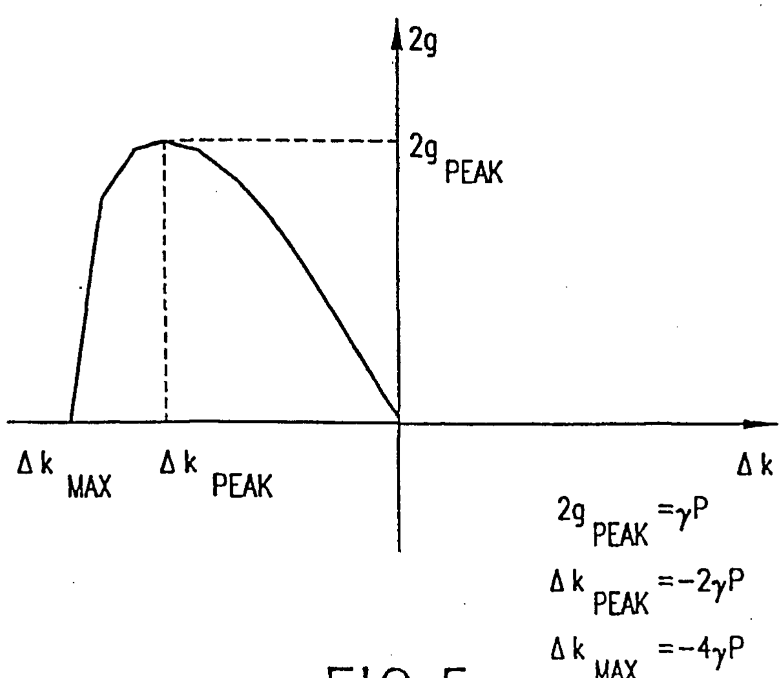

FIG.5

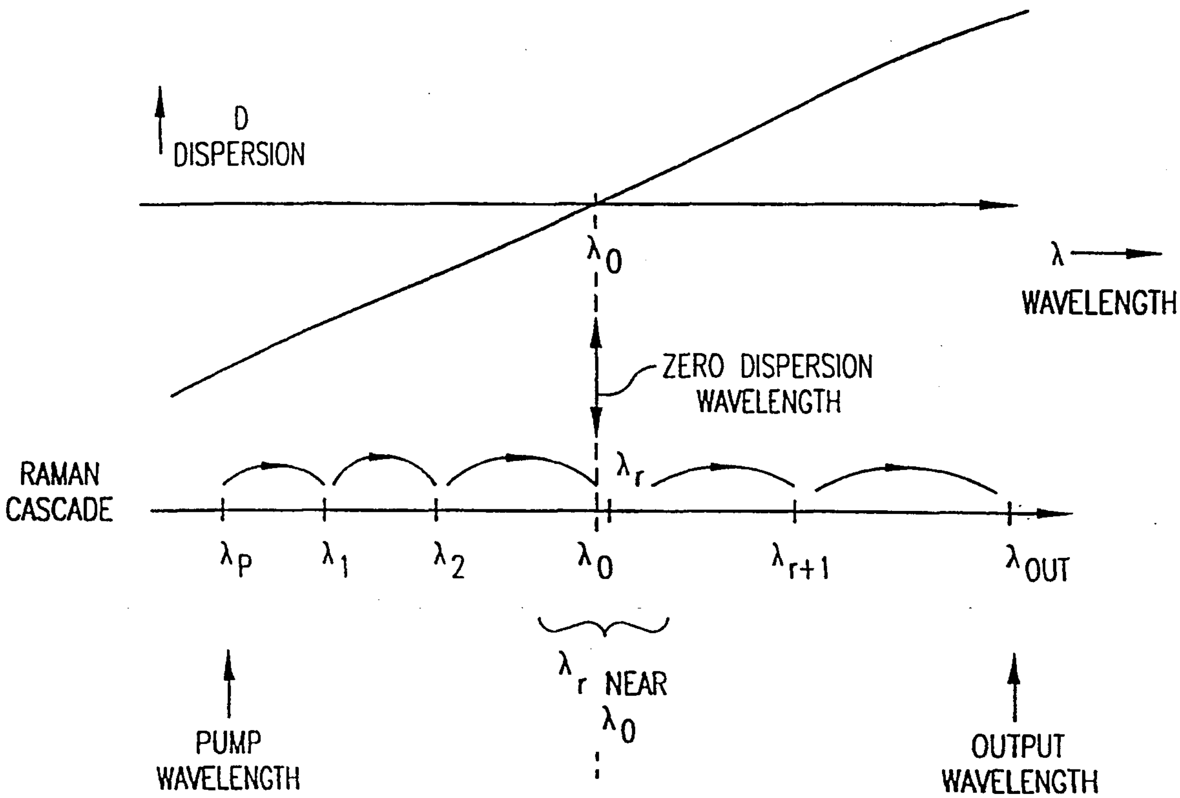
D
DISPERSION
λ_0
λ
WAVELENGTH
ZERO DISPERSION
WAVELENGTH
RAMAN
CASCADE
λ_r
λ_P
λ_1
λ_2
λ_0
λ_{r+1}
λ_{OUT}
λ_r NEAR
λ_0
PUMP
WAVELENGTH
OUTPUT
WAVELENGTH

FIG.6

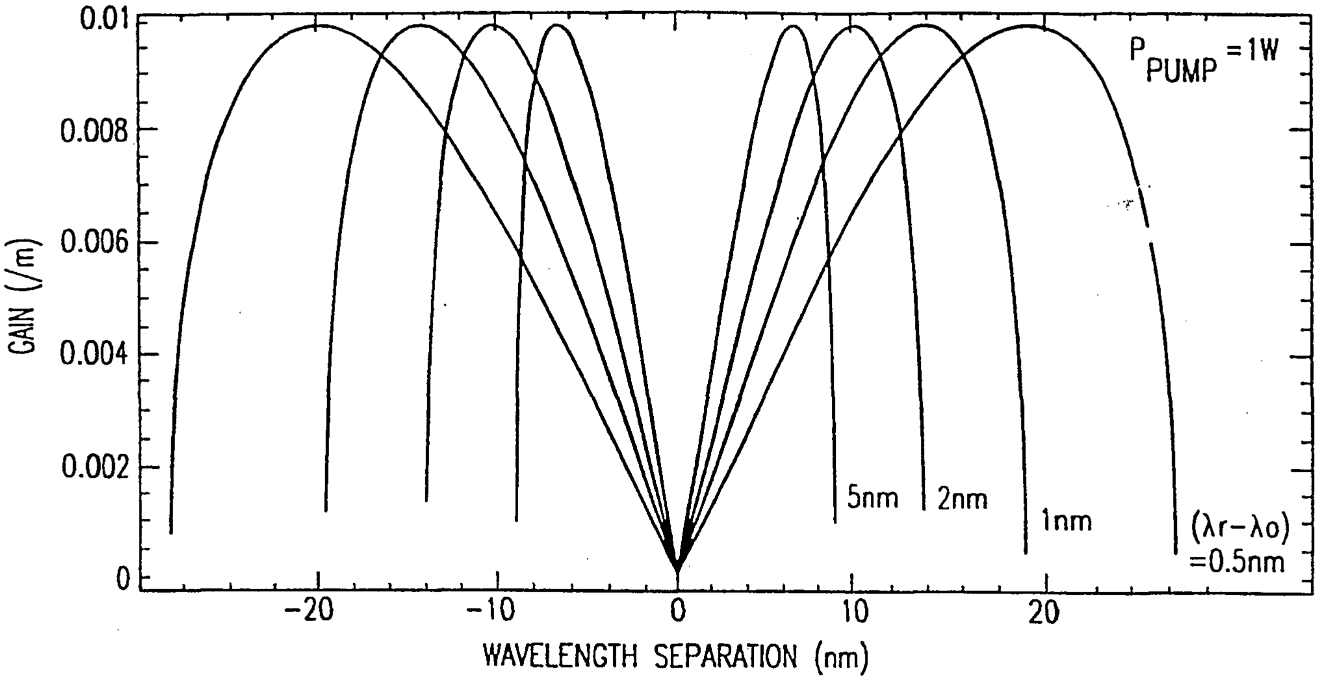
0.01
0.008
0.006
0.004
0.002
0
GAIN (/m)
P_{PUMP} = 1W
5nm
2nm
1nm
(λr−λo) =0.5nm
−20
−10
0
10
20
WAVELENGTH SEPARATION (nm)

FIG.7

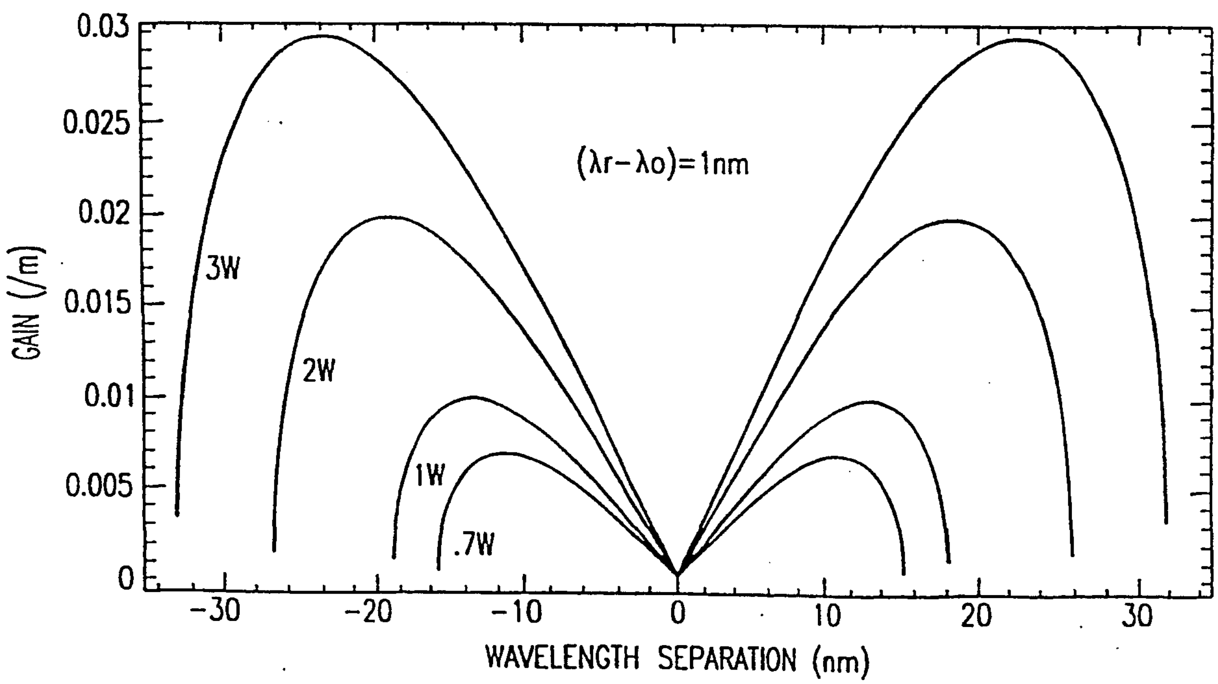
0.03
0.025
0.02
0.015
0.01
0.005
0
GAIN (/m)
(λr−λo)=1nm
3W
2W
1W
.7W
−30
−20
−10
0
10
20
30
WAVELENGTH SEPARATION (nm)

FIG.8

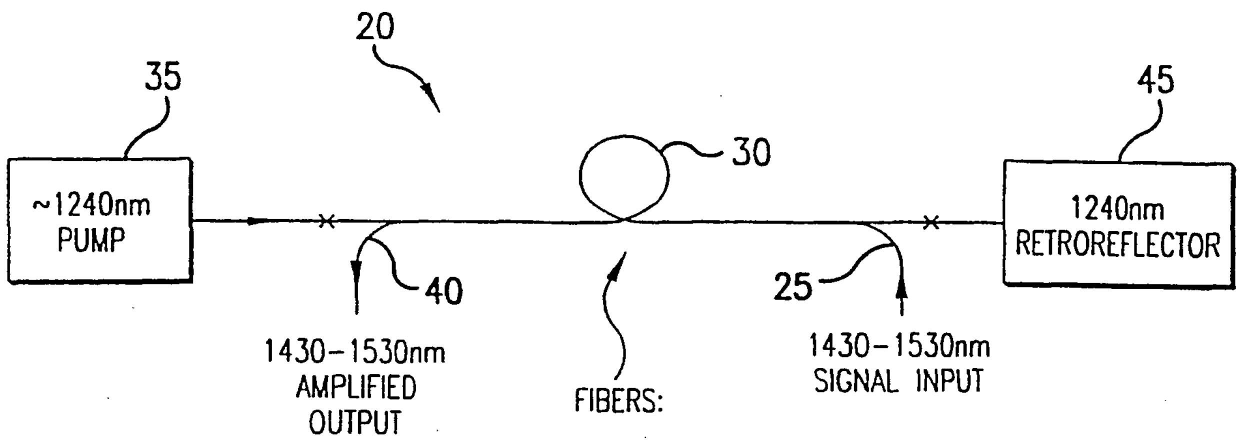

FIG.9

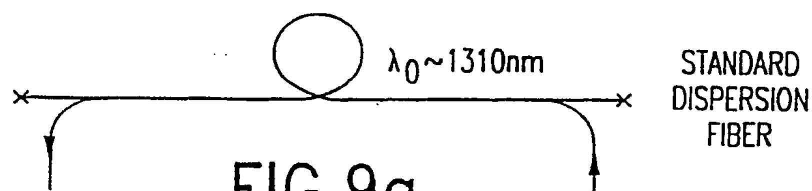

FIG.9a

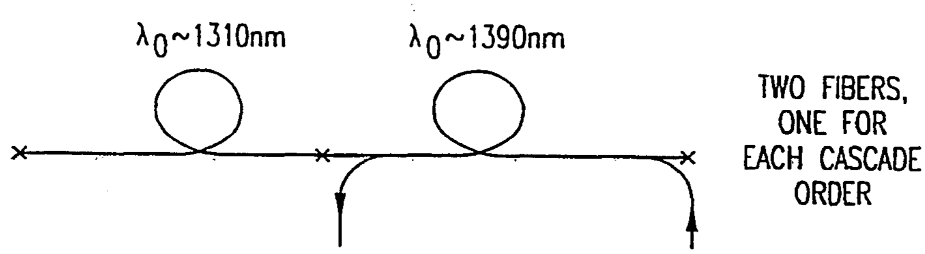

FIG.9b

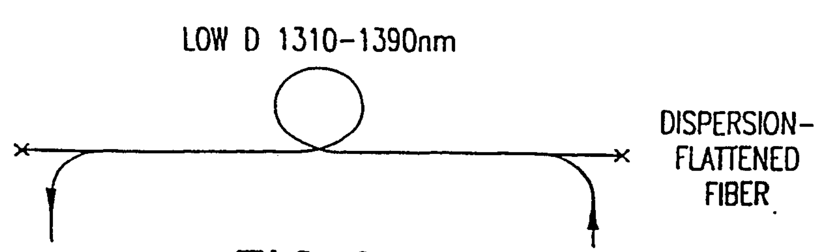

FIG.9c

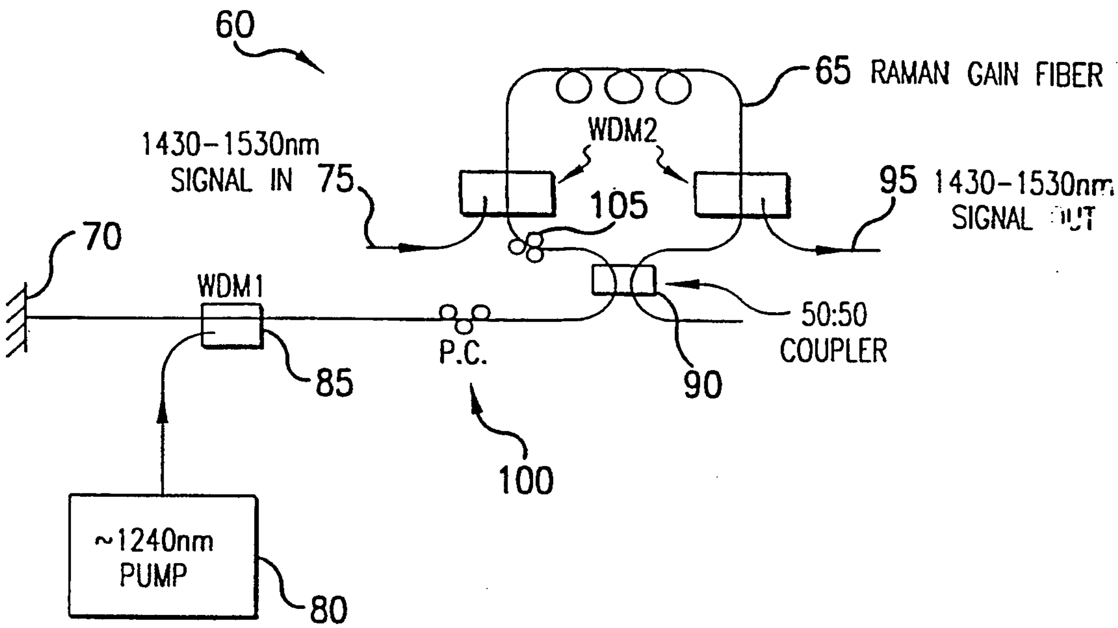
60
65 RAMAN GAIN FIBER
WDM2
1430-1530nm
SIGNAL IN 75
105
95 1430-1530nm
SIGNAL OUT
70
WDM1
50:50
COUPLER
85
P.C.
90
100
~1240nm
PUMP
80

FIG.10

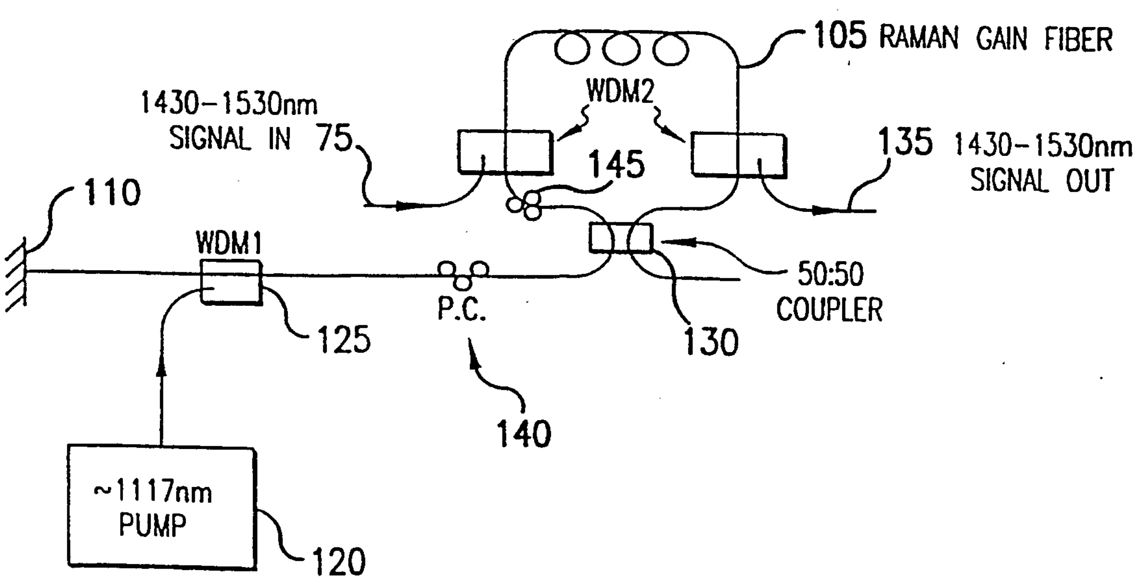
105 RAMAN GAIN FIBER
WDM2
1430-1530nm
SIGNAL IN 75
145
135 1430-1530nm
SIGNAL OUT
110
WDM1
50:50
COUPLER
125
P.C.
130
140
~1117nm
PUMP
120

FIG.11

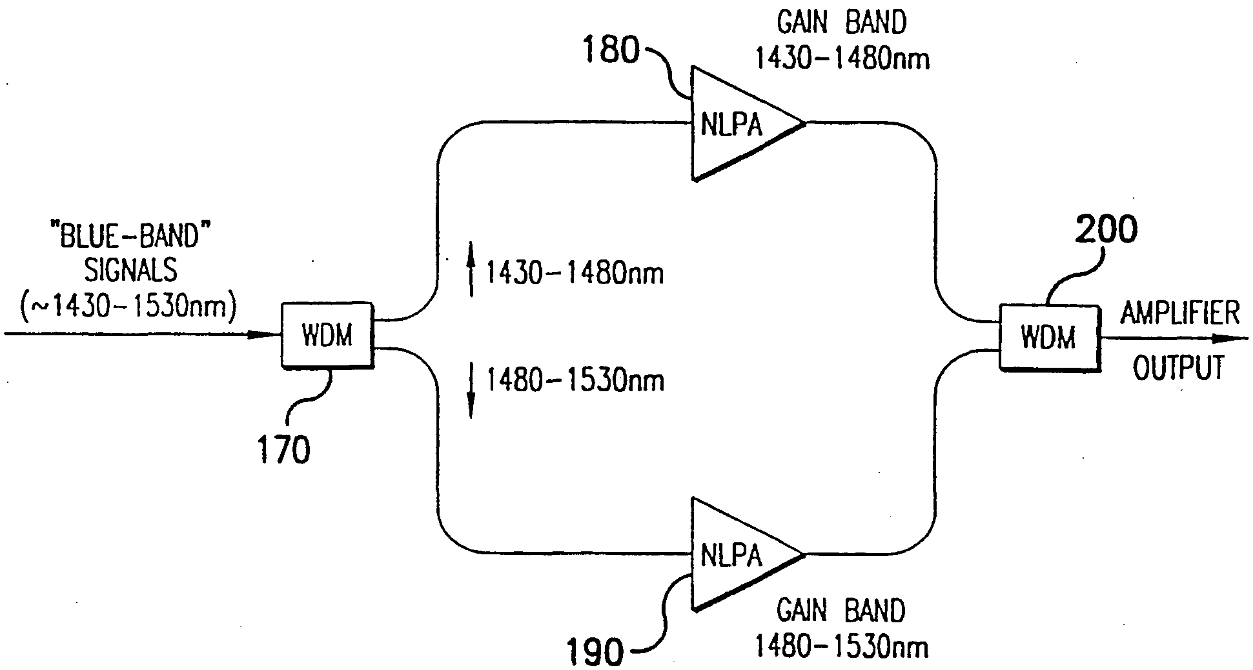
180
GAIN BAND
1430-1480nm
NLPA
"BLUE-BAND"
SIGNALS
(~1430-1530nm)
WDM
1430-1480nm
1480-1530nm
200
WDM
AMPLIFIER
OUTPUT
170
NLPA
GAIN BAND
1480-1530nm
190

FIG.12

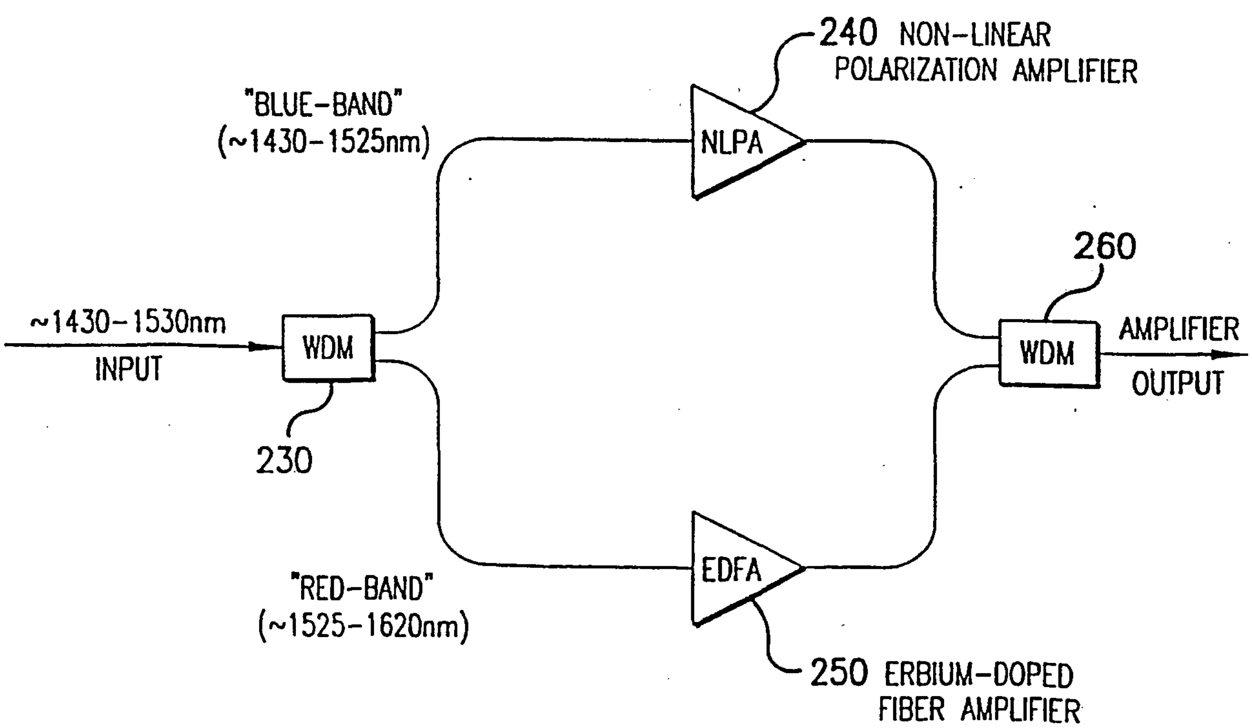
240 NON-LINEAR
POLARIZATION AMPLIFIER
"BLUE-BAND"
(~1430-1525nm)
NLPA
260
~1430-1530nm
INPUT
WDM
WDM
AMPLIFIER
OUTPUT
230
EDFA
"RED-BAND"
(~1525-1620nm)
250 ERBIUM-DOPED
FIBER AMPLIFIER

FIG.13

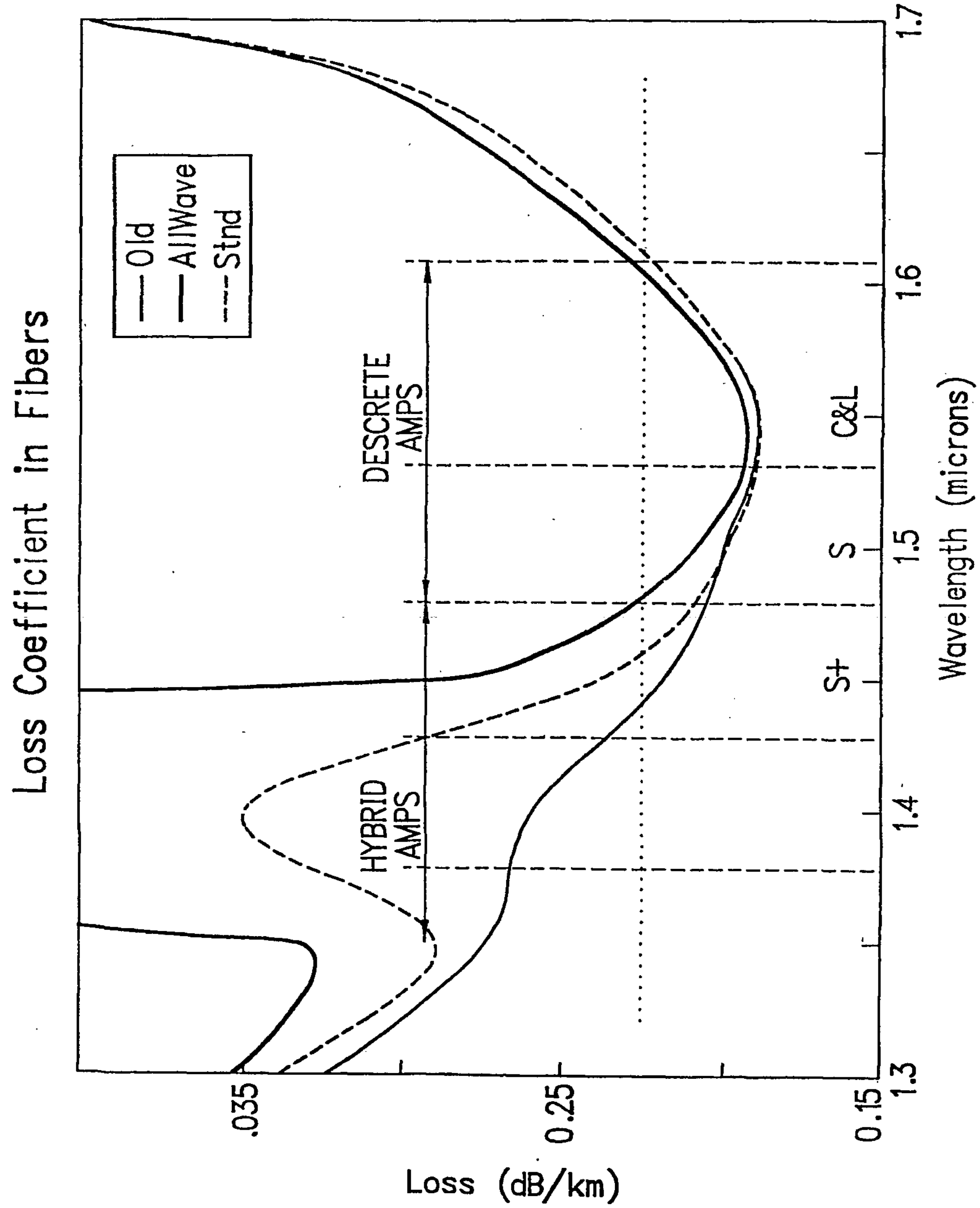
Loss Coefficient in Fibers
Old
AllWave
Stnd
DESCRETE AMPS
HYBRID AMPS
S+
S
C&L
Loss (dB/km)
.035
0.25
0.15
1.3
1.4
1.5
1.6
1.7
Wavelength (microns)

FIG. 14

1. Distributed Raman Amps is S+ band

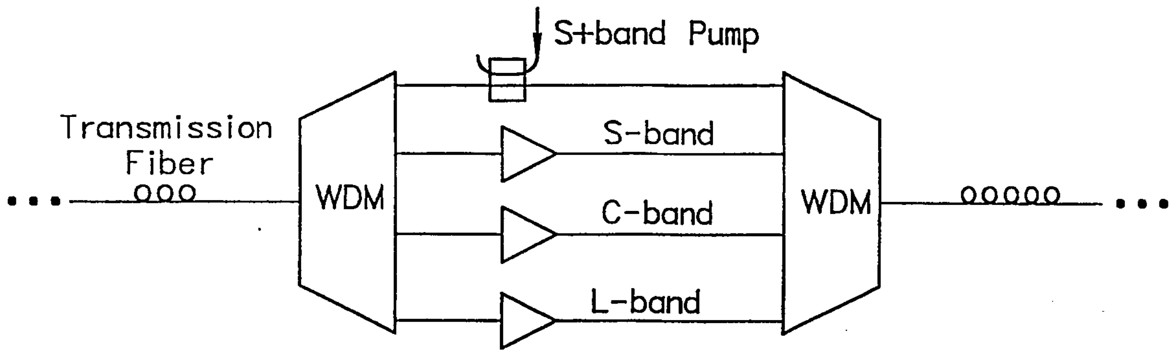

FIG. 15A

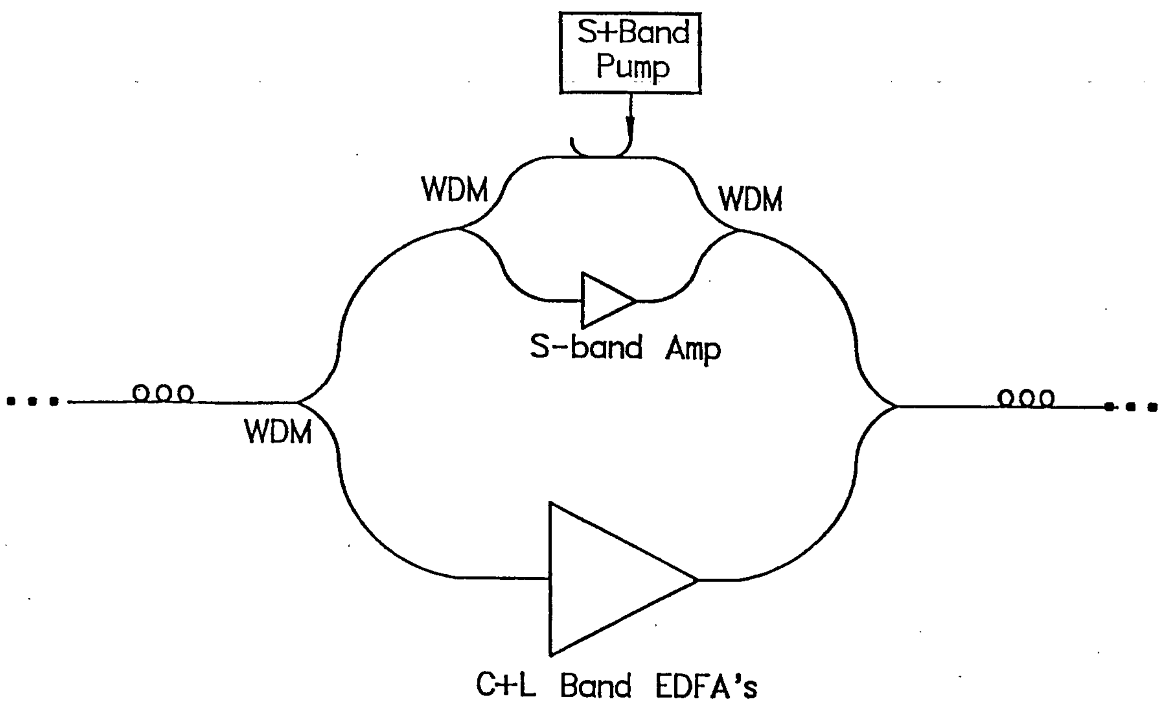

FIG. 15B

2. Hybrid Raman Amps in S+ band

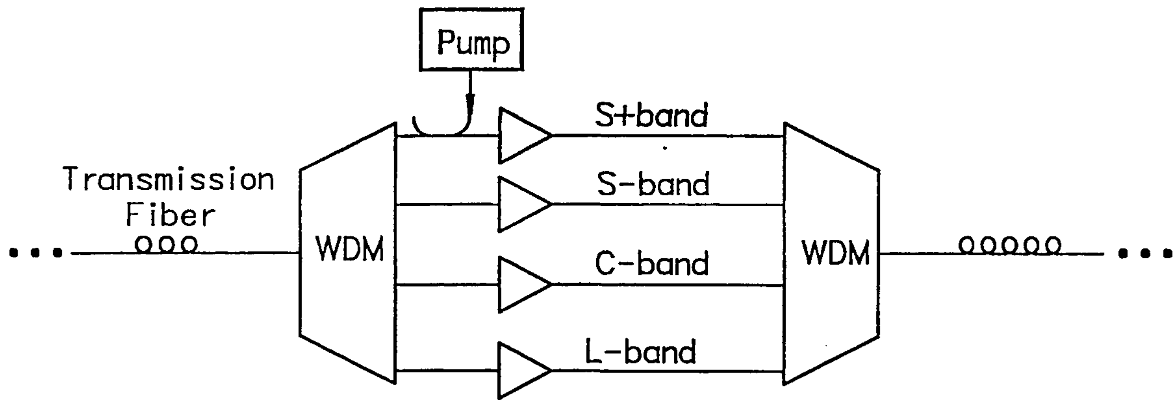

FIG. 16A

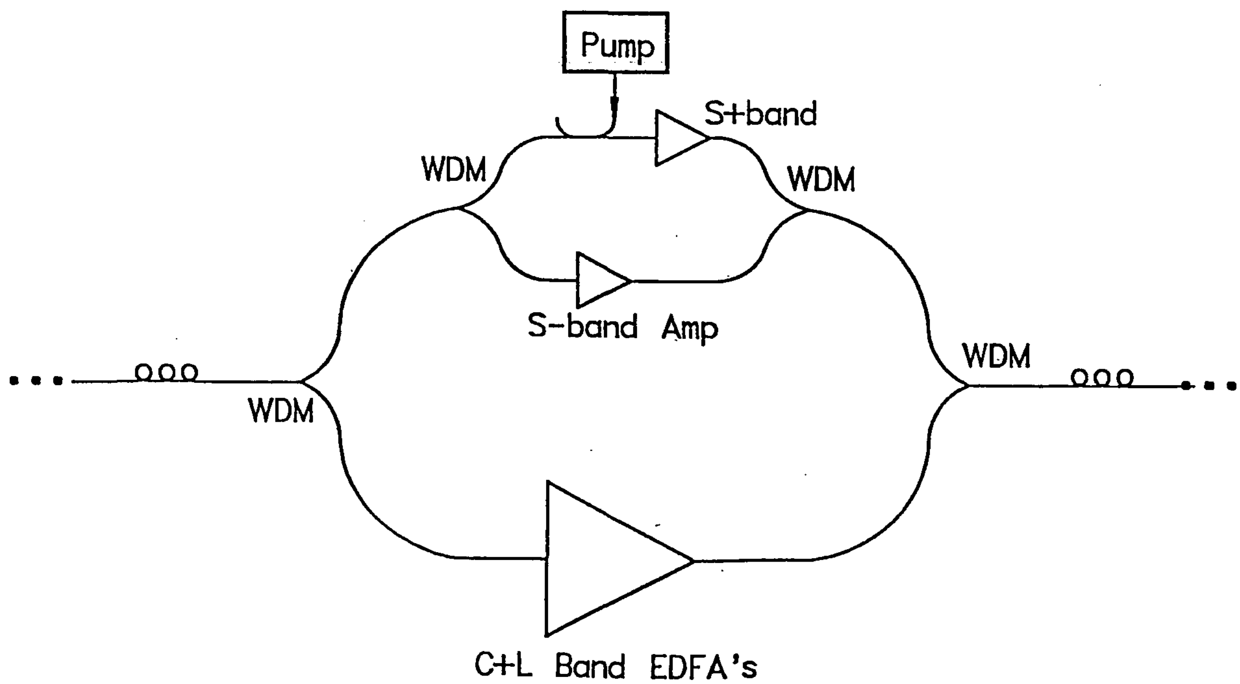

FIG. 16B

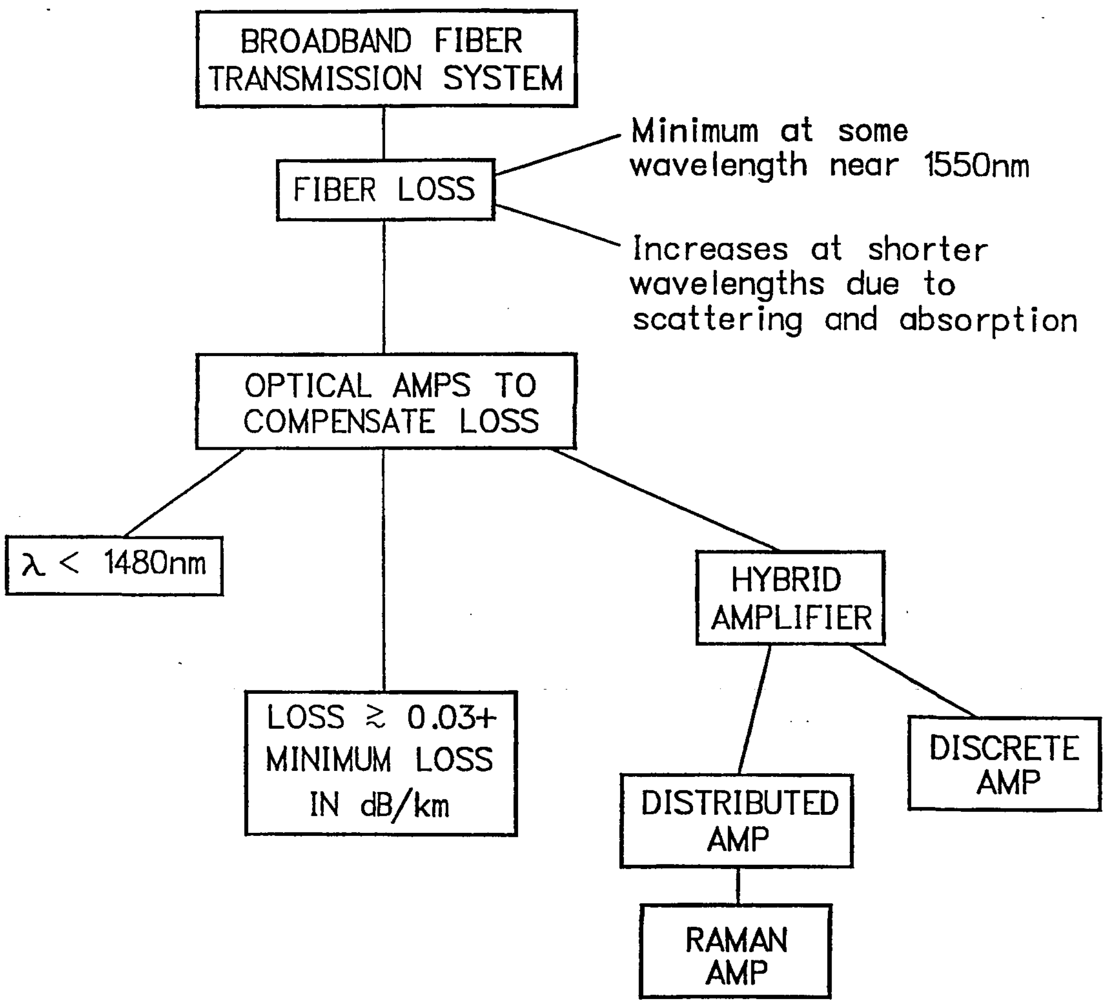
BROADBAND FIBER TRANSMISSION SYSTEM
FIBER LOSS
Minimum at some wavelength near 1550nm
Increases at shorter wavelengths due to scattering and absorption
OPTICAL AMPS TO COMPENSATE LOSS
λ < 1480nm
LOSS ≳ 0.03+ MINIMUM LOSS IN dB/km
HYBRID AMPLIFIER
DISTRIBUTED AMP
DISCRETE AMP
RAMAN AMP

FIG. 17

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8 August 2002 (08.08.2002)

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(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
09/765,972 19 January 2001 (19.01.2001) US

(63) Related by continuation (CON) or continuation-in-part (CIP) to earlier application:
US 09/765,972 (CON)
Filed on 19 January 2001 (19.01.2001)

(71) Applicant (*for all designated States except US*): XTERA COMMUNICATIONS, INC. [US/US]; 500 West Bethany Drive, Allen, TX 75013 (US).

(72) Inventor; and
(75) Inventor/Applicant (*for US only*): ISLAM, Mohammed, N. [US/US]; 907 Twin Creeks Drive, Allen, TX 75013 (US).

(74) Agent: KUBEHL, Douglas, M.; Baker Botts LLP, Suite 600, 2001 Ross Avenue, Dallas, TX 75201-2980 (US).

(81) Designated States (*national*): AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DZ, EC, EE, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, MZ, NO, NZ, OM, PH, PL, PT, RO, RU, SD, SE, SG, SI, SK, SL, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VN, YU, ZA, ZM, ZW.

(84) Designated States (*regional*): ARIPO patent (GH, GM, KE, LS, MW, MZ, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE, TR), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

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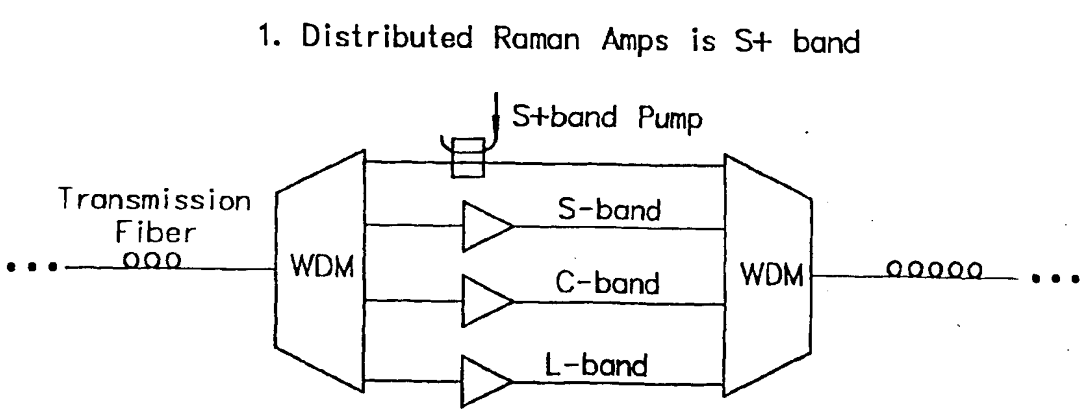
— *as to applicant's entitlement to apply for and be granted a patent (Rule 4.17(ii)) for the following designations AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DZ, EC, EE, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, MZ, NO, NZ, OM, PH, PL, PT, RO, RU, SD, SE, SG, SI, SK, SL, TJ, TM, TN, TR, TT, TZ, UA, UG, UZ, VN, YU, ZA, ZM, ZW, ARIPO patent (GH, GM, KE, LS, MW, MZ, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian patent*

[Continued on next page]

(54) Title: S+ BAND NONLINEAR POLARIZATION AMPLIFIERS



(57) Abstract: An amplified broadband optical signal is produced in a transmission system. An optical signal is divided into a first beam and a second beam. The first beam has a wavelength less than a predetermined wavelength. The second beam has a wavelength greater than the predetermined wavelength. The first beam is directed to a transmission link in the transmission system. The transmission system includes a distributed Raman amplifier. The distributed Raman amplifier operates in the wavelength range less than 1480 nm. The second beam is directed to a second amplifier. The first and second beams are combined. An amplified broadband optical signal is produced.

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(AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE, TR), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG)

— *as to the applicant's entitlement to claim the priority of the earlier application (Rule 4.17(iii)) for all designations*

Published:

— *with international search report*

(88) Date of publication of the international search report: 4 September 2003

For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

INTERNATIONAL SEARCH REPORT

International Application No
PCT/US 02/01804

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 H04B10/17 H01S3/30

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 H04B H01S

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, WPI Data, PAJ, INSPEC

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
P,L, X	WO 01 52372 A (FREEMAN MICHAEL ;ISLAM MOHAMMED N (US); XTERA COMMUNICATIONS INC () 19 July 2001 (2001-07-19) page 20, line 4 - line 18 page 30, line 11 - line 25 page 31, line 22 -page 33, line 33 page 40, line 18 - line 25 figures 5,12A,30,31,32A,32B,33A,33B ---	1-3, 5-22, 24-30, 32,33
X	WO 99 66607 A (BANDWIDTH SOLUTIONS INC ;ISLAM MOHAMMED AZIZUL (US); ISLAM MOHAMME) 23 December 1999 (1999-12-23) page 17, line 25 -page 18, line 7 page 34, line 13 -page 35, line 27 figure 15A --- -/--	9-33

[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

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Date of the actual completion of the international search	Date of mailing of the international search report
5 June 2003	20/06/2003

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL – 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Masche, C

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 6 151 160 A (NISSOV MORTEN ET AL) 21 November 2000 (2000-11-21) column 2, line 19 - line 60 column 5, line 9 - line 31 figure 4	1-8
A	US 6 101 024 A (HARRIS HAYDEN HENRY ET AL) 8 August 2000 (2000-08-08) the whole document	

INTERNATIONAL SEARCH REPORT

formation on patent family members

Inte onal Application No

PCT/US 02/01804

Patent document cited in search report		Publication date	Patent family member(s)			Publication date
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			CA	2400900	A1	19-07-2001
			EP	1250737	A1	23-10-2002
			WO	0152372	A1	19-07-2001
			US	2003016437	A1	23-01-2003
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			WO	9966607	A2	23-12-1999
			US	6359725	B1	19-03-2002
			US	2002063948	A1	30-05-2002
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			JP	2002508601	T	19-03-2002
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			WO	9949580	A2	30-09-1999
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			US	6239902	B1	29-05-2001
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			US	2002067537	A1	06-06-2002
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